

High energy astrophysics is one of the most important and exciting areas of contemporary astronomy, involving the most energetic phenomena in the universe. The highly acclaimed first and second editions of Professor Longair's series immediately established themselves as essential text books on high energy astrophysics. In this third edition, the subject matter is brought up to date and consolidated into a single volume covering Galactic, extragalactic and cosmological aspects of High Energy Astrophysics. The material is presented in four parts. The first provides the necessary astronomical background for understanding the context of high energy astrophysical phenomena. The second provides a thorough treatment the physical processes that govern the behaviour of particles and radiation in astrophysical environments such as interstellar gas, neutron stars, and black holes. The third part applies these tools to a wide range of high energy astrophysical phenomena in our own Galaxy, while the fourth and final part deals with extragalactic and cosmological aspects of high energy astrophysics.

This book assumes that readers have some knowledge of physics and mathematics at the undergraduate level, but no prior knowledge of astronomy is required. The new third edition of the book covers all aspects of modern high energy astrophysics to the point at which the key concerns of current research can be understood.



# High Energy Astrophysics

Third Edition

Malcolm S. Longair

*Emeritus Jacksonian Professor of Natural Philosophy,  
Cavendish Laboratory,  
University of Cambridge, Cambridge*



PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE  
The Pitt Building, Trumpington Street, Cambridge, United Kingdom  
CAMBRIDGE UNIVERSITY PRESS

The Edinburgh Building, Cambridge CB2 2RU, UK  
40 West 20th Street, New York, NY 10011-4211, USA  
477 Williamstown Road, Port Melbourne, VIC 3207, Australia  
Ruiz de Alarcón 13, 28014 Madrid, Spain  
Dock House, The Waterfront, Cape Town 8001, South Africa  
<http://www.cambridge.org>

© Cambridge University Press 1981, 1992, 1994, 1997, 2000, 2002, 2004

First published 1981

Second edition in two volumes 1992, 1994, reprinted with corrections 1997, 2000, 2002,  
2004

*British Library cataloguing in publication data*

Longair, M. S. (Malcolm S.)

High energy astrophysics.

I. Title

XXX.YYYYYY

ISBN 0 XXX YYYYYY Z hardback

Transferred to digital printing 2004

*For Deborah*

# Contents

<i>Preface</i>	<i>page</i> ii
<i>Acknowledgements</i>	v
<i>Figure credits</i>	vii
<i>Part I. Astronomical background</i>	1
1 High energy astrophysics – an introduction	3
1.1 High energy astrophysics and modern physics and astronomy	3
1.2 The sky in different astronomical wavebands	5
1.3 Optical waveband	7
1.4 Infrared waveband	10
1.5 Millimetre and submillimetre waveband	14
1.6 Radio waveband	19
1.7 Ultraviolet waveband	23
1.8 X-ray waveband	25
1.9 $\gamma$ -ray waveband	27
1.10 Cosmic ray astrophysics	29
1.11 Other non-electromagnetic astronomies	34
1.12 Concluding remarks	36
2 The stars and stellar evolution	39
2.1 Introduction	39
2.2 Basic observations	39
2.3 Stellar structure	43
2.4 The equations of energy generation and energy transport	48
2.5 The equations of stellar structure	53
2.6 The Sun as a star	56
2.7 Evolution of high and low mass stars	66
2.8 Stellar evolution on the colour-magnitude diagram	76
2.9 Mass loss	77

2.10	Conclusion	84
3	The galaxies	85
3.1	Introduction	85
3.2	The Hubble sequence	86
3.3	The red and blue sequences	89
3.4	Further correlations among the properties of galaxies	95
3.5	The masses of galaxies	98
4	Clusters of galaxies	109
4.1	The morphologies of rich clusters of galaxies	109
4.2	Clusters of galaxies and isothermal gas spheres	113
4.3	The Coma cluster of galaxies	117
4.4	Mass distribution of hot gas and dark matter in clusters	119
4.5	Cooling flows in clusters of galaxies	123
4.6	The Sunyaev-Zeldovich effect in hot intracluster gas	125
4.7	Gravitational lensing by galaxies and clusters of galaxies	129
4.8	Dark matter in galaxies and clusters of galaxies	135
	<i>Part II. Physical processes</i>	141
5	Ionisation losses	143
5.1	Introduction	143
5.2	Ionisation losses – non-relativistic treatment	144
5.3	The relativistic case	149
5.4	Practical forms of the ionisation loss formulae	154
5.5	Ionisation losses of electrons	158
5.6	Nuclear emulsions, plastics and meteorites	159
5.7	Dynamical friction	165
6	Radiation of accelerated charged particles and bremsstrahlung of electrons	169
6.1	Introduction	169
6.2	The radiation of accelerated charged particles	169
6.3	Bremsstrahlung	178
6.4	Non-relativistic bremsstrahlung energy loss rate	182
6.5	Thermal bremsstrahlung	183
6.6	Relativistic bremsstrahlung	189
7	The dynamics of charged particles in magnetic fields	195
7.1	A uniform static magnetic field	195
7.2	A time-varying magnetic field	197
7.3	The scattering of charged particles by irregularities in the magnetic field	202
7.4	The scattering of high energy particles by Alfvén and hydromagnetic waves	205
7.5	The diffusion-loss equation for high energy particles	207



8	Synchrotron radiation	213
8.1	The total energy loss rate	213
8.2	Non-relativistic gyroradiation and cyclotron radiation	216
8.3	The spectrum of synchrotron radiation – physical arguments	219
8.4	The spectrum of synchrotron radiation - a fuller version	223
8.5	The synchrotron radiation of a power law distribution of electron energies	233
8.6	The polarisation of synchrotron radiation	235
8.7	Synchrotron self-absorption	239
8.8	Useful numerical results	244
8.9	The radio emission of the Galaxy	246
9	Interactions of high energy photons	251
9.1	Photoelectric absorption	251
9.2	Thomson and Compton scattering	255
9.3	Inverse Compton scattering	261
9.4	Comptonisation	267
9.5	The Sunyaev-Zeldovich effect	282
9.6	Synchrotron–self Compton radiation	286
9.7	Cherenkov radiation	291
9.8	Electron–positron pair production	297
9.9	Electromagnetic showers	299
9.10	Electron-positron annihilation and positron production mechanisms	302
10	Nuclear interactions	307
10.1	Nuclear interactions and high energy astrophysics	307
10.2	Spallation cross-sections	310
10.3	Nuclear emission lines	315
10.4	Cosmic rays in the atmosphere	321
11	Aspects of plasma physics and magnetohydrodynamics	327
11.1	Elementary concepts in plasma physics	327
11.2	Magnetic flux freezing	334
11.3	Shock waves	344
11.4	The Earth’s magnetosphere	349
11.5	Magnetic buoyancy	352
11.6	Reconnection of magnetic lines of force	354
	<i>Part III. High Energy Astrophysics in our Galaxy</i>	361
12	Interstellar gas and magnetic fields	363
12.1	The interstellar medium in the life cycle of stars	363
12.2	Diagnostic tools - neutral interstellar gas	363
12.3	Ionised interstellar gas	370
12.4	Interstellar dust	378

12.5	An overall picture of the interstellar gas	387
12.6	Star formation	393
12.7	The Galactic magnetic field	402
13	Dead stars	413
13.1	Supernovae	414
13.2	White dwarfs, neutron stars and the Chandrasekhar limit	431
13.3	White dwarfs	438
13.4	Neutron stars	439
13.5	The discovery of neutron stars	444
13.6	The galactic population of neutron stars	458
13.7	Thermal emission of neutron stars	460
13.8	Pulsar glitches	461
13.9	The pulsar magnetosphere	464
13.10	The radio and high energy emission of pulsars	467
13.11	Black holes	469
14	Accretion power in astrophysics	483
14.1	Introduction	483
14.2	Accretion - general considerations	483
14.3	Thin accretion discs	491
14.4	Thick discs and advective flows	504
14.5	Accretion in binary systems	506
14.6	Accreting binary systems	516
14.7	Black holes in X-ray binaries	531
14.8	Final thoughts	537
15	Cosmic rays	539
15.1	The energy spectra of cosmic ray protons and nuclei	539
15.2	The abundances of the elements in the cosmic rays	543
15.3	The isotropy and energy density of cosmic rays	549
15.4	Gamma ray observations of the Galaxy	550
15.5	The origin of the light elements in the cosmic rays	554
15.6	The confinement time of cosmic rays in the Galaxy and cosmic ray clocks	563
15.7	The confinement volume for cosmic rays	565
15.8	The Galactic halo	568
15.9	The highest energy cosmic rays and extensive air-showers	571
15.10	Observations of the highest energy cosmic rays	573
15.11	The isotropy of ultra-high energy cosmic rays	578
15.12	The Greisen-Kuzmin-Zatsepin (GKZ) cut-off	581
16	The origin of cosmic rays in our Galaxy	585
16.1	Introduction	585
16.2	Energy loss processes for high energy electrons	585

16.3	diffusion-loss equation for high energy electrons	590
16.4	Supernova remnants as sources of high energy particles	594
16.5	The minimum energy requirements for synchrotron radiation	599
16.6	Supernova remnants as sources of high energy electrons	603
16.7	The evolution of supernova remnants	604
16.8	The adiabatic loss problem and the acceleration of high energy particles	607
17	The acceleration of high energy particles	613
17.1	General principles of acceleration	613
17.2	The acceleration of particles in solar flares	614
17.3	Fermi acceleration - original version	616
17.4	Diffusive shock acceleration in strong shock waves	621
17.5	Beyond the standard model	627
17.6	The highest energy cosmic rays	635
<i>Part IV. Extragalactic High Energy Astrophysics</i>		637
18	Active galaxies	639
18.1	Introduction	639
18.2	Radio galaxies and high energy astrophysics	639
18.3	The quasars	641
18.4	Seyfert galaxies	648
18.5	Blazars, superluminal sources and $\gamma$ -ray sources	651
18.6	Low Ionisation Nuclear Emission Regions (LINERS)	653
18.7	Ultra-Luminous Infrared Galaxies (ULIRGs)	654
18.8	X-ray Surveys of Active Galaxies	656
18.9	Unification Schemes for Active Galaxies	658
19	Black Holes in the Nuclei of Galaxies	667
19.1	The Properties of Black Holes	667
19.2	Elementary Considerations	669
19.3	Dynamical evidence for supermassive black holes in galactic nuclei	670
19.4	The Soltan Argument	681
19.5	Black holes and spheroid masses	683
19.6	X-ray observations of fluorescence lines in active galactic nuclei	685
19.7	The Growth of Black Holes in the Nuclei of Galaxies	693
20	The Vicinity of the Black Hole	697
20.1	The prime ingredients of active galactic nuclei	697
20.2	The continuum spectrum	697
20.3	The emission line regions – the overall picture	701
20.4	The narrow-line regions – the example of Cygnus A	702
20.5	The broad-line regions and reverberation mapping	707
20.6	The alignment effect and shock excitation of emission line regions	715

20.7	Accretion discs about supermassive black holes	718
21	Extragalactic Radio Sources	723
21.1	Extended Radio Sources – Fanaroff-Riley types	723
21.2	The astrophysics of FR2 radio sources	730
21.3	The FR1 radio sources	738
21.4	The microquasars	740
21.5	Jet physics	742
22	Compact extragalactic sources and superluminal motions	745
22.1	Compact radio sources	745
22.2	Superluminal motions	747
22.3	Relativistic beaming	750
22.4	The superluminal source population	759
22.5	Synchro-Compton Radiation and the Inverse Compton Catastrophe	763
22.6	$\gamma$ -ray Sources in Active Galactic Nuclei	764
22.7	$\gamma$ -ray bursts	771
23	Cosmological aspects of high energy astrophysics	781
23.1	The cosmic evolution of galaxies and active galaxies	781
23.2	The essential theoretical tools	783
23.3	The Evolution of non-thermal sources with cosmic epoch	787
23.4	The Evolution of thermal sources with cosmic epoch	798
23.5	Mid and far-infrared number counts	807
23.6	Submillimetre Number Counts	810
23.7	The global star formation rate	813
23.8	The Old Red Galaxies	817
23.9	Putting It All Together	819
A1	Astronomical conventions and nomenclature	825
A1.1	Galactic coordinates and projections of the celestial sphere onto a plane	825
A1.2	Distances in astronomy	829
A1.3	Masses in astronomy	832
A1.4	Flux densities, luminosities, magnitudes and colours	833
A1.5	Diffraction-limited telescopes	838
A1.6	Interferometry and synthesis imaging	845
A1.7	The sensitivities of astronomical detectors	848
A1.8	Units and relativistic notation	854
	<i>References</i>	858

# Preface

## Ancient history

It was a challenge to write this third edition of *High Energy Astrophysics*. Writing the first edition was great fun and that rather slim volume reflected rather closely the lecturing style I adopted in presenting high energy astrophysics to final-year undergraduates in the period 1973–7. Although the material was updated when the manuscript was sent to the press in 1980, the book remained in essence a lecture course (Longair, 1981). The reception of the book was encouraging and in due course a second edition was needed. The subject had advanced so rapidly during the 1980s and early 1990s that the material could not be comfortably contained within one volume. The aim was originally to complete the task in two volumes, but by the time the Volumes 1 and 2 were completed, I had only reached the edge of our own Galaxy (Longair, 1997b,c)<sup>†</sup>. Volume 3 was begun, but for various reasons, was not completed – the whole project was becoming somewhat unwieldy.

In the meantime, I completed three other major book-writing projects. The first of these was a new edition of *Theoretical Concepts in Physics* (Longair, 2003). Then, I completed *The Cosmic Century: A History of Astrophysics and Cosmology* (Longair, 2006). Finally, in 2008, the new edition of *Galaxy Formation* was published (Longair, 2008).

## The new edition

Since the second edition of *High Energy Astrophysics*, many of the subject areas have changed out of all recognition and new areas of astrophysical research have been opened up, for example, ultra-high energy  $\gamma$ -ray astronomy. The publication of *Theoretical Concepts in Physics*, *The Cosmic Century* and *Galaxy Formation* have made it feasible to condense the original plan of a three volume work into a single volume. In reorganising

<sup>†</sup> The original volumes of the second edition were first published in 1992 (Volume 1) and 1994 (Volume 2). Major revisions and corrections were included in the 1997 reprints of both volumes. I regard the 1997 reissues as the definite versions of the second edition.

the material, some hard decisions had to be taken, but the convenience of including everything in one volume is worth the sacrifice of some of the material from the second edition. The principal decisions were as follows:

- Much of the relevant historical material has been included in *The Cosmic Century* and so that material will not be repeated here. I make references to the appropriate sections of *The Cosmic Century* and other historical texts. I do this with considerable reluctance since the historical development of High Energy Astrophysics has influenced strongly the way in which the astrophysics has developed intellectually. History will not disappear completely, but it will not be as prominent as in the earlier editions.
- Much of the necessary material needed to obtain a modern view of galaxies and the large scale structure of the Universe is included in *Galaxy Formation*. In particular, there is no need to repeat much of the detailed discussion of galaxies and clusters, or the large scale structure and dynamics of the Universe. These topics are, however, central to many of the topics in this book and so summaries of the most important topics needed to understand the astronomical context of high energy astrophysics are provided in Part 1.
- There was a strong emphasis upon the origin of cosmic rays in the first two editions. I still consider this to be excellent material, particularly in the area of ultra-high energy cosmic rays, but it has been somewhat abbreviated in the new edition.
- There was also a considerable amount of material on detectors and telescopes in the earlier edition. I believe this material is of the greatest interest and importance in understanding our ability to make observations in different wavebands. This aspect of the subject has been strongly moderated in the new edition. These are fascinating topics, but modern telescopes and detectors have become increasingly complex and sophisticated. Summaries of a number of important topics in the physics of astronomical detectors and telescopes are included as an Appendix.
- In the second edition, I devoted some space to high energy astrophysics in the Solar System. This material has been abbreviated, but important topics such as the diffusion of energetic charged particles in the Solar Wind and the acceleration of charged particles in solar flares have been preserved.
- The opportunity has been taken to rationalise the presentation of the physical and astrophysical processes so that duplication of material is avoided.
- The writing has been very considerably tightened up so that the discussion is less discursive than in the earlier editions. Again, I regret the necessity of doing this since often these asides provide valuable physical insights for the reader new to the subject.

The aims of the present edition are the same as the earlier editions. A very wide range of physical processes relevant for high energy astrophysics is discussed, the emphasis being strongly upon the understanding of the underlying physics. I aim to maintain the informal style of the earlier editions and have no hesitation about using the first person singular

or expressing my personal opinion about the material under discussion. The emphasis is strongly upon physical principles and the discussion of general results rather than particular models which may have only ephemeral appeal.

As I learned during the writing of *The Cosmic Century*, physics and astrophysics have a symbiotic relation. On the one hand, the astrophysical sciences are concerned with the application of the laws of physics to phenomena on a large-scale in a Universe. On the other hand, new laws of physics are discovered and tested through astronomical observations and their astrophysical interpretation. In these ways, the new astrophysics, of which high energy astrophysics is one of the most important ingredients, is just as much a part of modern physics as laboratory physics.

Although there is limited scope for deviation from the central theme in this new edition, one of my original aims was to give the reader a feeling of what it is like to undertake research at the limits of present understanding. Astrophysics is fortunate in that many of the fundamental problems can be understood without a great deal of new physics or new physical concepts. Thus, the text may also be considered as introduction to the way in which research is carried out in the astrophysical context.

Above all, however, this material is not only mind-stretching, but also great fun. I have no intention of inhibiting my enthusiasm and enormous enjoyment of the physics and astrophysics for its own sake.

Malcolm Longair  
Cambridge and Venice  
January 2010.

## Acknowledgements

There are many people whom it is a pleasure to thank for help and advice during the preparation of this volume. Just as the first edition was begun during a visit to the Osservatorio Astronomico di Arcetri in Florence in April 1980, so the second edition could not have been completed without the Regents' Fellowship of the Smithsonian Institution which I held at the Harvard-Smithsonian Astrophysical Observatory during the period April–June 1990. I am particularly grateful to Professors Irwin Shapiro and Giovanni Fazio for sponsoring this visit to Harvard during which time the final drafts of Chapters 1–10 of the first volume of the second edition were completed. During that period, I had particularly helpful discussions with Drs Eugene Avrett, George Rybicki, Giovanni Fazio, Margaret Geller and many others. I am particularly grateful to them for their advice.

Much of the preliminary rewriting was completed while I was at the Royal Observatory, Edinburgh. Among the many colleagues with whom I discussed the contents of this volume, I must single out Dr John Peacock who provided deep insights into many topics. In completing the final chapter on the high energy astrophysics of the Solar System, I greatly benefitted from the advice of Professors John Brown, Carole Jordan and Eric Priest. Not only did they point me in the correct directions but they also reviewed my first drafts of that chapter. I am especially grateful to them for this laborious task. Many colleagues made helpful suggestions about corrections and additions to the first addition among whom Dr Roger Chevalier provided an especially useful list.

Coincidentally, the writing of the third edition began while I was a visitor at the Osservatorio Astronomico di Arcetri in Florence during the period April to June 2007. I thank Professor Francesco Palla and his colleagues for their hospitality during that visit. The catalogue of friends and colleagues who have continued to contribute to my understanding of high energy astrophysics and astrophysical cosmology since the publication of the second edition is enormous. Many of them are acknowledged in my recent books, but the list is so long that I would be bound to miss someone out. I acknowledge particular insights from my colleagues in the course of the book. Special thanks are due to Dr. David Green for his



expert advice, not only on supernova remnants, but also on the more arcane idiosyncracies of LaTeX.

To all of these friends and colleagues I make the usual disclaimer that any misrepresentations of the material presented in this book is entirely my responsibility and not theirs. Finally, I acknowledge the unfailing support and love of my family, Deborah, Mark and Sarah who have contributed much more than they will ever know to the completion of this book.

## Figure credits

I am most grateful to the authors of the papers which include the figures reproduced in this book for permission to reproduce them. The publishers have been equally helpful in allowing use of the figures. Each publisher has a specific form of acknowledgement requested and I include them all in the following list of the source of the figures. In the text itself, the usual abbreviated form of reference is used and full details of the publications are included in the bibliography. The sources of the figures used are as follows:

*Academic Press.* Reproduced by permission of Academic Press. Figs. A1.10 and A1.12.

*Addison-Wesley.* Reproduced by permission of Pearson Education Addison-Wesley Figs. 6.5 and 9.18.

*Advances in Space Research.* Reproduced by permission of Advances in Space Research and Elsevier B.V. Figs. 4.8 and 14.26.

*Annual Review of Astronomy and Astrophysics.* Reproduced by permission of Annual Reviews, Inc. Figs. 4.7, 7.4, 12.4, 12.7, 12.8, 14.25, 14.27, 15.7, 17.10, 22.18, 22.19, 22.21, 23.7, 23.8, 23.18(a) and A1.11.

*Annual Review of Nuclear and Particle Physics.* Reproduced by permission of Annual Reviews, Inc. Figs. 1.16, 5.8 and 5.9.

*Astronomical Journal.* Reproduced by permission of the American Astronomical Society. Figs. 4.4, 18.3, 22.10, 22.11, 23.6, 23.12, 23.15 and 23.19.

*Astronomical Society of the Pacific Conference Series.* Reproduced by permission of the Astronomical Society of the Pacific. Fig. 21.4.

*Astronomy and Astrophysics.* Reproduced with permission ©ESO. Figs. 2.25, 4.6, 9.10, 12.14(a), 13.18, 14.9, 14.21, 14.23, 15.8, 15.15, 18.8, 22.12, 23.9, 23.16 and A1.6.

*Astronomy and Astrophysics Reviews.* Reproduced with permission of Springer-Verlag. Figs. 4.13, 21.9 and 23.2.

*Astronomy and Astrophysics Supplement Series.* Reproduced with permission ©ESO. Fig. 2.29.

*Astronomy and Geophysics.* Reproduced with permission of Astronomy and Geophysics. Fig. 23.3.

*Astroparticle Physics.* Reproduced by permission of Astroparticle Physics and Elsevier B.V. Fig. 17.8.

*Astrophysical Journal.* Reproduced by permission of the American Astronomical Society. Figs. 2.2, 2.4(a), 2.24, 2.26, 3.4, 3.5, 3.8, 3.10, 3.12, 3.13, 8.3, 9.1, 9.2, 9.13, 9.14, 9.15, 11.13, 12.5, 12.6, 12.11, 12.19, 12.20, 13.17, 13.23, 14.2, 14.4, 14.5, 14.18, 15.9, 15.14, 15.24, 16.4(b), 16.5, 16.6, 17.5, 18.1, 18.5(b), 18.14, 18.15, 19.1, 19.3, 20.8, 21.10, 21.5, 21.6, 22.13, 22.15, 22.7, 22.8, 22.20 and 23.22.

*Astrophysical Journal Letters.* Reproduced by permission of the American Astronomical Society. Figs. 10.8, 13.6(b), 17.6, 17.7, 19.7, 21.8, 21.13, 22.9 and 22.14.

*Astrophysical Journal Supplement Series.* Reproduced by permission of the American Astronomical Society. Figs. 12.10, 14.15, 15.13(a) and 18.11.

*Astrophysics and Space Science Reviews.* Reproduced by permission of Cambridge Scientific Publishers Ltd. Fig. 9.9.

*Australian Astronomical Observatory (AAO).* Reproduced by permission of the Australian Astronomical Observatory (AAO). Figs. 4.2, 13.4 and 18.2.

*Australian Telescope National Facility (ATNF).* Reproduced by permission of the Australian Telescope National Facility (ATNF). Figs. 13.8(b) and 13.16.

*Cambridge University.* Reproduced by permission of Cambridge University. Fig. 16.2.

*Cambridge University Press.* Reproduced by permission of Cambridge University Press. Figs. 1.1(a) and(b), 2.3, 2.6, 2.7, 2.12, 2.18, 2.19, 10.7, 11.10, 11.11, 11.12, 13.13, 13.15, 13.20, 13.21, 14.1, 14.3(b), 14.8, 14.10, 14.14, 14.16, 14.19, 14.22, 19.8, 20.1, 20.5, 20.6, 20.11, 21.1(b), 22.3, 23.13, 23.23, A1.8 and A1.9.

*European Southern Observatory.* Reproduced courtesy of the European Southern Observatory. Figs. 12.13, 12.14(b) and 13.5.

*European Space Agency.* Reproduced courtesy of the European Space Agency. Figs. 2.1, 2.9(b), 2.10, 2.11(a) and (b) and 10.5. (see also *NASA, ESA and the STScI*)

*European Space Agency and NASA.* Reproduced courtesy of the European Space Agency (ESA) and the US National Aeronautics and Space Administration (NASA). Fig. 11.5.

*Freeman and Co..* Reproduced courtesy of W.H. Freeman and Company, New York. Fig. A1.4.

*Hanlon, William.* Reproduced courtesy of Dr. William Hanlon. <http://www.physics.utah.edu/~whanlon/spectrum.html>. Fig. 15.1.

*Institut d'Astrophysique Publications.* Reproduced courtesy of the Institut d'Astrophysique, Paris. Fig. 14.20.

*International Cosmic Ray Conference Series.* Reproduced courtesy of the International Cosmic Ray Conference Series (ICRC). Figs. 15.6, 15.21, 15.22 and 15.23.

*Journal of Physics: Conference Series.* Reproduced courtesy of the Institute of Physics. Fig. 15.17.

*LAMBDA programme of Goddard Space Flight Center (GSFC) of NASA.* We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA). Support for LAMBDA is provided by the NASA Office of Space Science. Figs. 1.8 and 1.11. 4.12

*Living Reviews in Relativity.* Reproduced courtesy of Living Reviews. Fig. 4.12.

*Max-Planck-Institut für Extraterrestrische Physik.* Reproduced courtesy of Professor J. Trümper and the Max-Planck-Institut für Extraterrestrische Physik. Figs. 1.13(b), 4.5 and 13.9(b).

*Max-Planck-Institut für Radioastronomie.* Reproduced courtesy of Professor R. Wielebinski and the Max-Planck-Institut für Radioastronomie. Figs. 1.9 and 12.17.

*Mellinger, Axel.* Reproduced courtesy of Dr. Axel Mellinger. <http://home.arcor-online.de/axel.mellinger/>. Figs. 1.2(a) and (b).

*Memoirs of the Royal Astronomical Society (MemRAS).* Reproduced by permission of Memoirs of the Royal Astronomical Society. Fig. 12.18.

*Monthly Notices of the Royal Astronomical Society (MNRAS).* Reproduced by permission of Monthly Notices of the Royal Astronomical Society. Figs. 3.6, 3.7, 3.9, 3.14, 4.9, 8.13, 13.7, 16.8, 16.9, 16.10, 18.4, 18.6, 19.7, 19.9, 19.11, 20.9, 20.10, 21.11, 21.14, 23.5, 23.10, 23.14, 23.17, 23.18(b) and (c).

*NASA.* Reproduced courtesy of the US National Aeronautics and Space Administration (NASA). Figs. 1.4(a), 1.5, 1.6, 1.7, 1.12, 1.13(a), 1.14, 11.4, 14.3(a), 16.4(a), 21.1(c), 22.16 and 22.17.

*NASA, ESA and the STScI.* Reproduced courtesy of the US National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and Space Telescope Science Institute (STScI). Figs. 1.10, 2.22, 2.28, 2.29, 3.2(a)-(d), 3.3(a) and (b), 4.1, 12.14(c), 13.8(a), 13.8(b), 18.10, 18.13, 19.1 and 19.2.

*NASA, ESA, STScI and Chandra Science Team.* Reproduced courtesy of the US National Aeronautics and Space Administration (NASA), the European Space Agency (ESA),

Space Telescope Science Institute (STScI) and the Chandra Science Team. Figs. 13.1 and 13.3.

*National Radio Astronomy Observatory (NRAO)*. Reproduced by permission of the National Radio Astronomy Observatory (NRAO) and the Associated Universities Inc. (AUI). Figs. 16.3, 21.2, 21.3 and 22.2.

*Nature*. Reproduced courtesy of the Nature Publishing Group. Figs. 2.23, 3.1, 4.14, 8.4, 10.9, 13.6(a), 13.28, 13.29, 16.5, 19.4, 19.5, 19.6, 22.2, 21.12, 22.20, 23.11 and 23.24.

*Nature Reference Publishing and the Institute of Physics*. Reproduced courtesy of the Nature Publishing Group and the Institute of Physics. Fig. 2.30.

*Nobeyama Radio Observatory*. Reproduced courtesy of Professor R. Tatematsu and the Nobeyama Radio Observatory. Fig. 12.12(b).

*Orosz, Jerome*. Reproduced courtesy of Professor Jerome Orosz. <http://mintaka.sdsu.edu/faculty/orosz/web/>. Figs. 13.27 and 13.30.

*Nuclear Physics A*. Reproduced courtesy of Nuclear Physics A and Elsevier B.V. Fig. 10.6.

*Palomar Observatories*. Reproduced courtesy of the Palomar Observatories. Figs. 4.1 and 13.9(a).

*Particle Data Group*. C. Amsler et al. (Particle Data Group), Physics Letters B667, 1 (2008) and 2009 partial update for the 2010 edition. Figs. 5.6, 5.7, 9.20, 10.11, 15.2, 15.3 and 15.19.

*Pergamon Press*. Reproduced courtesy of Pergamon Press and Elsevier B.V.. Fig. 10.2.

*Physica Scripta*. Reproduced courtesy of Physica Scripta. Figs. 4.11 and 18.5(a).

*Physical Review C and D*. Reproduced courtesy of Physical Review and American Institute of Physics. C: Fig. 10.4(a) and (b) and D: Fig. 2.13.

*Physical Review Letters*. Reproduced courtesy of Physical Review Letters. Figs. 2.14(a) and (b), 2.15 and 15.21.

*Physics Letters B*. Reproduced courtesy of Physics Letters B and Elsevier B.V.. Fig. 15.20.

*Physics Today*. Reproduced courtesy of Physics Today and the American Institute of Physics. Fig. 13.2.

*Pierre Auger Observatory*. Reproduced courtesy of Professor Alan Watson and the Pierre Auger Observatory. Fig. 15.18.

*Princeton University Press.* Reproduced courtesy of Princeton University Press. Fig. 12.9.

*Publications of the Astronomical Society of Japan.* Reproduced courtesy of the Astronomical Society of Japan. Fig. 23.21.

*Publications of the Astronomical Society of the Pacific.* Reproduced courtesy of the Astronomical Society of the Pacific. Fig. 2.4(b).

*Quarterly Journal of the Royal Astronomical Society (QJRAS).* Reproduced by permission of Quarterly Journal of the Royal Astronomical Society. Figs. 4.3 and 13.14.

*Radiocarbon.* Reproduced courtesy of Radiocarbon. Fig. 10.12.

*Reviews of Modern Physics.* Reproduced by permission of Reviews of Modern Physics. Figs. 9.2(a) and 9.20(a).

*Rubin, Vera.* Reproduced courtesy of Professor Vera Rubin. Fig. 3.11.

*Springer-Verlag.* With kind permission of Springer Science+Business Media. Figs. 1.15(a) and (b), 2.8, 2.16, 2.17, 2.20, 2.21, 5.10(b), 6.3, 9.11, 9.12, 10.3(c), 12.2, 12.16(a), 12.16(b), 13.10, 13.11, 14.12, 14.17, 15.4, 15.5, 15.11, 15.12, 15.13(b), 15.23, 18.9, 23.20, 23.4 and A1.5.

*Two Micron All Sky Survey.* This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. Fig. 1.4(b).

*University of Arizona Press.* Reproduced courtesy of University of Arizona Press. Fig. 5.10(a).

*University Science Books .* Reproduced courtesy of University Science Books. Figs. 20.3, 20.4 and 20.7.

*Wiley.* Reproduced courtesy of John Wiley and Sons, Inc. Figs. 5.4, 6.2, 8.2, 8.6, 8.7, 13.12, 13.22, 14.11, 14.13, 18.7 and 19.12.

*Yale University Press.* Reproduced courtesy of Yale University Press. Fig. 13.26.

































## References

- Aaronson, M. & Mould, J. (1983). A Distance Scale from the Infrared Magnitude/H I Velocity-width Relation. IV – The Morphological Type Dependence and Scatter in the Relation; the Distances to Nearby Groups, *Astrophysical Journal*, **265**, 1–17.
- Abdo, A. A., Ackermann, M., Ajello, M., et al. (2009a). Early Fermi Gamma-ray Space Telescope Observations of the Quasar 3C 454.3, *Astrophysical Journal*, **699**, 817–823.
- Abdo, A. A., Ackermann, M., Ajello, M., et al. (2009b). Bright Active Galactic Nuclei Source List from the First Three Months of the Fermi Large Area Telescope All-Sky Survey, *Astrophysical Journal*, **700**, 597–622.
- Abdurashitov, J. N., Bowles, T. J., Cleveland, B. T., et al. (2003). Measurement of the Solar Neutrino Capture Rate in Sage, *Nuclear Physics B Proceedings Supplements*, **118**, 39–46.
- Abdurashitov, J. N., Veretenkin, E. P., Vermul, V. M., et al. (2002). Solar neutrino flux measurements by the Soviet-American gallium experiment (SAGE) for half the 22-year solar cycle, *Soviet Journal of Experimental and Theoretical Physics*, **95**, 181–193.
- Abell, G. O. (1958). The Distribution of Rich Clusters of Galaxies, *Astrophysical Journal Supplement*, **3**, 221–288.
- Abell, G. O., Corwin Jr, H. G., & Olowin, R. P. (1989). A Catalogue of Rich Clusters of Galaxies, *Astrophysical Journal Supplement*, **70**, 1–138.
- Abraham, J., Abreu, P., Aglietta, M., & Pierre Auger Consortium (2010a). Measurement of the depth of maximum of extensive air showers above  $10^{18}$  eV, *Physical Review Letters*, **104**, 091101(1–7).
- Abraham, J., Abreu, P., Aglietta, M., & Pierre Auger Consortium (2010b). Measurement of the energy spectrum of cosmic rays above  $10^{18}$  eV using the Pierre Auger Array, *Physics Letters*, **B685**, 239–246.
- Abraham, R. G., Tanvir, N. R., Santiago, B., et al. (1996). Galaxy morphology to  $I = 25$  mag in the Hubble Deep Field, *Monthly Notices of the Royal Astronomical Society*, **279**, L47–L52.
- Abramovitz, M. & Stegun, I. A. (1965). *Handbook of mathematical functions*. New York: Dover Publications.
- Abramowicz, M. A., Jaroszyński, M., & Sikora, M. (1978). Relativistic, Accreting Disks, *Astronomy and Astrophysics*, **63**, 221–224.
- Adams, F. C., Lada, C. J., & Shu, F. H. (1987). Spectral evolution of young stellar objects, *Astrophysical Journal*, **312**, 788–806.
- Adams, F. C. & Shu, F. H. (1985). Infrared emission from protostars, *Astrophysical Journal*, **296**, 655–669.
- Afonso, C., Albert, J. N., Andersen, J., et al. (2003). Limits on Galactic Dark Matter with 5 years of EROS SMC data, *Astronomy and Astrophysics*, **400**, 951–956.
- Aharonian, F., Akhperjanian, A. G., Anton, G., et al. (2009). Simultaneous Observations of PKS

- 2155-304 with HESS, Fermi, RXTE, and Atom: Spectral Energy Distributions and Variability in a Low State, *Astrophysical Journal Letters*, **696**, L150–L155.
- Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. (2007a). An Exceptional Very High Energy Gamma-Ray Flare of PKS 2155-304, *Astrophysical Journal Letters*, **664**, L71–L74.
- Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. (2006). A low level of extragalactic background light as revealed by  $\gamma$ -rays from blazars, *Nature*, **440**, 1018–1021.
- Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. (2007b). H.E.S.S. Observations of the Supernova Remnant RX J0852.0-4622: Shell-Type Morphology and Spectrum of a Widely Extended Very High Energy Gamma-Ray Source, *Astrophysical Journal*, **661**, 236–249.
- Aharonian, F. A., Akhperjanian, A. G., Aye, K.-M., et al. (2004). High-energy particle acceleration in the shell of a supernova remnant, *Nature*, **432**, 75–77.
- Ahmad, Q. R., Allen, R. C., Andersen, T. C., et al. (2002). Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory, *Physical Review Letters*, **89**, 011301–(1–5).
- Aitken, D. K., Smith, C. H., James, S. D., et al. (1988). 10 Micron Spectral Observations of SN 1987A – The First Year, *Monthly Notices of the Royal Astronomical Society*, **235**, 19P–31P.
- Akerib, D. S., Attisha, M. J., Bailey, C. N., et al. (2006). Limits on Spin-Independent Interactions of Weakly Interacting Massive Particles with Nucleons from the Two-Tower Run of the Cryogenic Dark Matter Search, *Physical Review Letters*, **96**, 011302–+.
- Alcock, C., Akerlof, C. W., Allsman, R. A., et al. (1993a). Possible Gravitational Microlensing of a Star in the Large Magellanic Cloud, *Nature*, **365**, 621–623.
- Alcock, C., Allsman, R. A., Alves, D. R., et al. (2000). The MACHO Project: Microlensing Results from 5.7 Years of Large Magellanic Cloud Observations, *Astrophysical Journal*, **542**, 281–307.
- Alcock, C., Allsman, R. A., Axelrod, T. S., et al. (1993b). The MACHO Project – a Search for the Dark Matter in the Milky-Way, in *Sky Surveys: Protostars to Protogalaxies*, ed. Soifer, T., pp. 291–296. San Francisco: Astronomical Society of the Pacific Conference Series.
- Alexander, P. (2006). Models of young powerful radio sources, *Monthly Notices of the Royal Astronomical Society*, **368**, 1404–1410.
- Alexander, P., Brown, M. T., & Scott, P. F. (1984). A multi-frequency radio study of Cygnus A, *Monthly Notices of the Royal Astronomical Society*, **209**, 851–868.
- Alfvén, H. & Herlofson, N. (1950). Cosmic Radiation and Radio Stars, *Physical Review*, **78**, 616.
- Aliu, E., Andringa, S., Aoki, S., et al. (2005). Evidence for Muon Neutrino Oscillation in an Accelerator-Based Experiment, *Physical Review Letters*, **94**(8), 081802–+.
- Aloisio, R., Berezhinsky, V., & Gazizov, A. (2009). Ultra high energy cosmic rays: the disappointing model, in *Proceedings of the 31st International Cosmic Ray Conference (Lodz, Poland)*, ed. XX, pp. XX–XX. XX.
- Amsler, C., Doser, M., Antonelli, M., et al. (2008). Review of Particle Physics, *Physics Letters B*, **667**, 1–5. These data can be found at <http://pdg.lbl.gov>.
- Anderson, C. (1932). The Apparent Existence of Easily Deflected Positives, *Science*, **76**, 238–239.
- Anderson, C. & Neddermeyer, S. (1936). Cloud Chamber Observations of Cosmic Rays at 4300 Metres Elevation and Near Sea-Level, *Physical Review*, **50**, 263–271.
- Antoni, T., Apel, W. D., Badea, A. F., et al. (2005). KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems, *Astroparticle Physics*, **24**, 1–25.
- Antonucci, R. R. (1993). Unified Models for Active Galactic Nuclei and Quasars, *Annual Review of Astronomy and Astrophysics*, **31**, 473–521.
- Antonucci, R. R. & Miller, J. S. (1985). Spectropolarimetry and the Nature of NGC 1068, *Astrophysical Journal*, **297**, 621–632.
- Arnett, D. (2004). Stellar Nucleosynthesis: A Status Report 2003, in *Origin and Evolution of the Elements*, eds McWilliam, A. & Rauch, M., pp. 12–26. Cambridge: Cambridge University Press.
- Arnett, W. D. & Clayton, D. D. (1970). Explosive Nucleosynthesis in Stars, *Nature*, **227**, 780–784.

- Arzoumanian, Z., Chernoff, D. F., & Cordes, J. M. (2002). The Velocity Distribution of Isolated Radio Pulsars, *Astrophysical Journal*, **568**, 289–301.
- Ashie, Y., Hosaka, J., Ishihara, K., et al. (2005). Measurement of atmospheric neutrino oscillation parameters by Super-Kamiokande I, *Physical Review D*, **71**, 112005–+.
- Aublin, J. D. (2009). Discriminating potential astrophysical sources of the highest energy cosmic rays with the Pierre Auger Observatory, in *Proceedings of the 31st International Cosmic Ray Conference (Lodz, Poland)*, ed. XX, pp. XX–XX. XX.
- Auger, P., Ehrenfest Jr., P., Maze, R., et al. (1939). Extensive Air Showers, *Reviews of Modern Physics*, **11**, 288–291.
- Axford, W. I., Leer, E., & Skadron, G. (1977). The Acceleration of Cosmic Rays by Shock Waves, *Proceedings of the 15th International Cosmic Ray Conference*, **11**, 132–135.
- Baade, W. & Minkowski, R. (1954). Identification of the Radio Sources in Cassiopeia, Cygnus A, and Puppis A, *Astrophysical Journal*, **119**, 206–214.
- Babbedge, T. S. R., Rowan-Robinson, M., Vaccari, M., et al. (2006). Luminosity functions for galaxies and quasars in the Spitzer Wide-area Infrared Extragalactic Legacy Survey, *Monthly Notices of the Royal Astronomical Society*, **370**, 1159–1180.
- Backer, D. C., Kulkarni, S. R., Heiles, C., Davis, M. M., & Goss, W. M. (1982). A millisecond pulsar, *Nature*, **300**, 615–618.
- Bahcall, J. N. (1989). *Neutrino Astrophysics*. Cambridge: Cambridge University Press.
- Bahcall, J. N. & Bethe, H. (1990). A Solution of the Solar Neutrino Problem, *Physical Review Letters*, **65**, 2233–2235.
- Bahcall, J. N., Kirhakos, S., Saxe, D. H., & Schneider, D. P. (1997a). Hubble Space Telescope Images of a Sample of 20 Nearby Luminous Quasars, *Astrophysical Journal*, **479**, 642–658.
- Bahcall, J. N., Pinsonneault, M. H., Basu, S., & Christensen-Dalsgaard, J. (1997b). Are Standard Solar Models Reliable?, *Physical Review Letters*, **78**, 171–174.
- Bahcall, N. A. (1977). Clusters of galaxies, *Annual Review of Astronomy and Astrophysics*, **15**, 505–540.
- Bahcall, N. A., Dong, F., Hao, L., et al. (2003a). The Richness-dependent Cluster Correlation Function: Early Sloan Digital Sky Survey Data, *Astrophysical Journal*, **599**, 814–819.
- Bahcall, N. A., McKay, T. A., Annis, J., et al. (2003b). A Merged Catalog of Clusters of Galaxies from Early Sloan Digital Sky Survey Data, *Astrophysical Journal Supplement*, **148**, 243–274.
- Balbus, S. A. & Hawley, J. F. (1991). A Powerful Local Shear Instability in Weakly Magnetized Disks. I – Linear Analysis. II – Nonlinear Evolution, *Astrophysical Journal*, **376**, 214–233.
- Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. (2004). Quantifying the Bimodal Color-Magnitude Distribution of Galaxies, *Astrophysical Journal*, **600**, 681–694.
- Ballard, K. R. & Heavens, A. F. (1992). Shock acceleration and steep-spectrum synchrotron sources, *Monthly Notices of the Royal Astronomical Society*, **259**, 89–94.
- Band, D. L. & Grindlay, J. E. (1985). The Synchrotron-self Compton process in spherical geometries. I. Theoretical framework, *Astrophysical Journal*, **298**, 128–146.
- Barthel, P. D. (1989). Is Every Quasar Beamed?, *Astrophysical Journal*, **336**, 606–611.
- Barthel, P. D. (1994). Unified Schemes of FR2 Radio Galaxies and Quasars, in *First Stromlo Symposium: Physics of Active Galactic Nuclei*, eds Bicknell, G. V., Dopita, M. A., & Quinn, P. J., pp. 175–186. San Francisco: ASP Conference Series, Vol. 54.
- Batchelor, G. (1970). *An introduction to fluid dynamics*. Cambridge: Cambridge University Press.
- Bearden, J. A. & Burr, A. F. (1967). Reevaluation of X-ray Atomic Energy Levels, *Reviews of Modern Physics*, **39**, 125–142.
- Beck, R., Brandenburg, A., Moss, D., Shukurov, A., & Sokoloff, D. (1996). Galactic Magnetism: Recent Developments and Perspectives, *Annual Review of Astronomy and Astrophysics*, **34**, 155–206.
- Beck, R., Carilli, C. L., Holdaway, M. A., & Klein, U. (1994). Multifrequency observations of the radio continuum emission from NGC 253. I: Magnetic fields and rotation measures in the bar

- and halo, *Astronomy and Astrophysics*, **292**, 409–424.
- Beckwith, S. V. W., Stiavelli, M., Koekemoer, A. M., et al. (2006). The Hubble Ultra Deep Field, *Astronomical Journal*, **132**, 1729–1755.
- Begelman, M. C. (1996). *Baby Cygnus As*, pp. 209–214.
- Bekefi, G. (1966). *Radiation Processes in Plasmas*. New York: John Wiley and Sons.
- Bell, A. R. (1978). The Acceleration of Cosmic Rays in Shock Fronts. I, *Monthly Notices of the Royal Astronomical Society*, **182**, 147–156.
- Bell, A. R. (2004). Turbulent amplification of magnetic field and diffusive shock acceleration of cosmic rays, *Monthly Notices of the Royal Astronomical Society*, **353**, 550–558.
- Bell, A. R. (2005). The interaction of cosmic rays and magnetized plasma, *Monthly Notices of the Royal Astronomical Society*, **358**, 181–187.
- Bell, A. R. & Lucek, S. G. (2001). Cosmic ray acceleration to very high energy through the non-linear amplification by cosmic rays of the seed magnetic field, *Monthly Notices of the Royal Astronomical Society*, **321**, 433–438.
- Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. (2003). The Optical and Near-Infrared Properties of Galaxies: I. Luminosity and Stellar Mass Functions, *Astrophysical Journal Supplement Series*, **149**, 289–312.
- Bell-Burnell, J. (1983). The discovery of pulsars, in *Serendipitous discoveries in radio astronomy*, eds Kellermann, K. & Sheets, B., pp. 160–170. Green Bank, West Virginia: National Radio Astronomy Publications.
- Bender, R., Burstein, D., & Faber, S. M. (1993). Dynamically Hot Galaxies II. Global Stellar Populations, *Astrophysical Journal*, **411**, 153–169.
- Bennett, C., Halpern, M., Hinshaw, G., et al. (2003). First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results, *Astrophysical Journal Supplement Series*, **148**, 1–27.
- Bennett, C. L., Banday, A. J., Gorski, K. M., et al. (1996). Four-Year COBE DMR Cosmic Microwave Background Observations: Maps and Basic Results, *Astrophysical Journal*, **464**, L1–L4.
- Benson, B. A., Church, S. E., Ade, P. A. R., et al. (2004). Measurements of Sunyaev-Zel'dovich Effect Scaling Relations for Clusters of Galaxies, *Astrophysical Journal*, **617**, 829–846.
- Beresnyak, A., Jones, T. W., & Lazarian, A. (2009). Turbulence-induced magnetic fields and the structure of Cosmic Ray modified shocks, *ArXiv e-prints*.
- Berezhko, E. G. & Völk, H. J. (2007). Spectrum of Cosmic Rays Produced in Supernova Remnants, *Astrophysical Journal Letters*, **661**, L175–L178.
- Berezinsky, V. (2007). On origin of ultra high energy cosmic rays, *Astrophysics and Space Science*, **309**, 453–463.
- Berger, K., Majumdar, P., Lindfors, E., et al. (2009). MAGIC observations of the distant quasar 3C279 during an optical outburst in 2007, *ArXiv e-prints*.
- Best, P. N., Bailer, D. M., Longair, M. S., & Riley, J. M. (1995). Radio source asymmetries and unified schemes, *Monthly Notices of the Royal Astronomical Society*, **275**, 1171–1184.
- Best, P. N., Longair, M. S., & Röttgering, H. J. A. (1996). Evolution of the Aligned Structures in  $z \sim 1$  Radio Galaxies, *Monthly Notices of the Royal Astronomical Society*, **280**, L9–L12.
- Best, P. N., Longair, M. S., & Röttgering, H. J. A. (1997). HST, Radio and Infrared Observations of 28 3CR Radio Galaxies at Redshift  $z \sim 1$ . I - The Observations, *Monthly Notices of the Royal Astronomical Society*, **292**, 758–794.
- Best, P. N., Longair, M. S., & Röttgering, H. J. A. (1998). HST, Radio and Infrared Observations of 28 3CR Radio Galaxies at Redshift  $z$  approximately equal to 1. II – Old Stellar Populations in Central Cluster Galaxies, *Monthly Notices of the Royal Astronomical Society*, **295**, 549–567.
- Best, P. N., Longair, M. S., & Röttgering, H. J. A. (2000). Ionization, Shocks and Evolution of the Emission-Line Gas of Distant 3CR Radio Galaxies, *Monthly Notices of the Royal Astronomical Society*, **311**, 23–36.



- Bethe, H. & Heitler, W. (1934). On the Stopping of Fast Particles and on the Creation of Positive Electrons, *Proceedings of the Royal Society of London*, **A146**, 83–112.
- B  thermin, M., Dole, H., Beelen, A., & Aussel, H. (2010). Spitzer Deep and Wide Legacy Mid- and Far-Infrared Number Counts and Lower Limits of Cosmic Infrared Background, *ArXiv e-prints*.
- Bignami, G. F., Caraveo, P. A., Luca, A. D., & Mereghetti, S. (2003). The magnetic field of an isolated neutron star from X-ray cyclotron absorption lines, *Nature*, **423**, 725–727.
- Bildsten, L., Chakrabarty, D., Chiu, J., et al. (1997). Observations of Accreting Pulsars, *Astrophysical Journal Supplement Series*, **113**, 367–408.
- Binney, J. (1978). On the Rotation of Elliptical Galaxies, *Monthly Notices of the Royal Astronomical Society*, **183**, 501–514.
- Binney, J. & Merrifield, M. (1998). *Galactic Astronomy*. Princeton: Princeton University Press.
- Binney, J. & Tremaine, S. (2008). *Galactic Dynamics*. Princeton: Princeton University Press.
- Biretta, J. A., Sparks, W. B., & Macchetto, F. (1999). Hubble Space Telescope Observations of Superluminal Motion in the M87 Jet, *Astrophysical Journal*, **520**, 621–626.
- Biretta, J. A., Zhou, F., & Owen, F. N. (1995). Detection of Proper Motions in the M87 Jet, *Astrophysical Journal*, **447**.
- Blaauw, A., Gum, C. S., Pawsey, J. L., & Westerhout, G. (1959). Note: Definition of the New I.A.U. System of Galactic Co-Ordinates, *Astrophysical Journal*, **130**, 702–703.
- Blackett, P. & Occhialini, G. (1933). Some Photographs of the Tracks of Penetrating Radiation, *Proceedings of the Royal Society of London*, **A139**, 699–722.
- Blain, A. W. & Longair, M. S. (1993). Sub-Millimetre Cosmology, *Monthly Notices of the Royal Astronomical Society*, **264**, 509–521.
- Blain, A. W. & Longair, M. S. (1996). Observing Strategies for Blank-field Surveys in the Sub-Millimetre Waveband, *Monthly Notices of the Royal Astronomical Society*, **279**, 847–858.
- Blandford, R. & Eichler, D. (1987). Particle Acceleration at Astrophysical Shocks - a Theory of Cosmic-Ray Origin, *Physics Reports*, **154**, 1–75.
- Blandford, R. D. (1990). Physical processes in active galactic nuclei., in *Active Galactic Nuclei*, eds Blandford, R. D., Netzer, H., Woltjer, L., Courvoisier, T. J.-L., & Mayor, M., pp. 161–275.
- Blandford, R. D. (1994). Holes, Disks, Stars and Jets in Active Galactic Nuclei, in *The Physics of Active Galaxies*, ed. G. V. Bicknell, M. A. Dopita, . P. J. Q., volume 54 of *Astronomical Society of the Pacific Conference Series*, pp. 23–32.
- Blandford, R. D. & Begelman, M. C. (1999). On the fate of gas accreting at a low rate onto a black hole, *Monthly Notices of the Royal Astronomical Society*, **303**, L1–L5.
- Blandford, R. D. & McKee, C. F. (1982). Reverberation mapping of the emission line regions of Seyfert galaxies and quasars, *Astrophysical Journal*, **255**, 419–439.
- Blandford, R. D. & Narayan, R. (1992). Cosmological Applications of Gravitational Lensing, *Annual Review of Astronomy and Astrophysics*, **30**, 311–358.
- Blandford, R. D. & Ostriker, J. P. (1978). Particle Acceleration by Astrophysical Shocks, *Astrophysical Journal*, **221**, L29–L32.
- Blandford, R. D. & Rees, M. J. (1974). A 'twin-exhaust' model for double radio sources, *Monthly Notices of the Royal Astronomical Society*, **169**, 395–415.
- Blandford, R. D. & Znajek, R. L. (1977). Electromagnetic Extraction of Energy from Kerr Black Holes, *Monthly Notices of the Royal Astronomical Society*, **179**, 433–456.
- Blanton, M. R., Hogg, D. W., Bahcall, N. A., et al. (2003). The Broadband Optical Properties of Galaxies with Redshifts  $0.02 \leq z \leq 0.22$ , *Astrophysical Journal*, **594**, 186–207.
- Blumenthal, G. R. & Gould, R. J. (1970). Bremsstrahlung, Synchrotron Radiation, and Compton Scattering of High-Energy Electrons Traversing Dilute Gases, *Reviews of Modern Physics*, **42**, 237–271.
- Bolton, C. T. (1972). Identifications of CYG X-1 with HDE 226868, *Nature*, **235**, 271–273.
- Bondi, H. (1952). On spherically symmetrical accretion, *Monthly Notices of the Royal*

- Astronomical Society*, **112**, 195–204.
- Bondi, H. & Hoyle, F. (1944). On the mechanism of accretion by stars, *Monthly Notices of the Royal Astronomical Society*, **104**, 273–282.
- Born, M. & Wolf, E. (1999). *Principles of Optics*, 7th edition. Cambridge: Cambridge University Press.
- Bosma, A. (1981). 21-cm Line Studies of Spiral Galaxies. II. The Distribution and Kinematics of Neutral Hydrogen in Spiral Galaxies of Various Morphological Types., *Astronomical Journal*, **86**, 1825–1846.
- Bothe, W. & Kolhörster, W. (1929). The Nature of the High-altitude Radiation, *Zeitschrift für Physik*, **56**, 751–777.
- Bouwens, R. J., Illingworth, G. D., Blakeslee, J. P., & Franx, M. (2006). Galaxies at  $z \sim 6$ : The UV Luminosity Function and Luminosity Density from 506 HUDF, HUDF Parallel ACS Field, and GOODS i-Dropouts, *Astrophysical Journal*, **653**, 53–85.
- Boyle, B. J., Griffiths, R. E., Shanks, T., Stewart, G. C., & Georgantopoulos, I. (1993). A deep ROSAT survey. I - The QSO X-ray luminosity function, *Monthly Notices of the Royal Astronomical Society*, **260**, 49–58.
- Boyle, B. J., Shanks, T., Croom, S. M., et al. (2000). The 2dF QSO Redshift Survey – I. The Optical Luminosity Function of Quasi-Stellar Objects, *Monthly Notices of the Royal Astronomical Society*, **317**, 1014–1022.
- Braccesi, A., Formigini, L., & Gandolfi, E. (1970). Magnitudes, Colours and Coordinates of 175 Ultraviolet Excess Objects in the Field  $13^{\text{h}}$ ,  $+36^{\circ}$ , *Astronomy and Astrophysics*, **5**, 264–279. Erratum: *Astronomy and Astrophysics*, **23**, 159.
- Bracewell, R. (1986). *The Fourier Transform and its Applications*. New York: McGraw–Hill Book Company.
- Brandt, W. N. & Hasinger, G. (2005). Deep Extragalactic X-Ray Surveys, *Annual Review of Astronomy and Astrophysics*, **43**, 827–859.
- Browne, I. W. A. & Murphy, D. W. (1987). Beaming and the X-ray, optical and radio properties of quasars, *Monthly Notices of the Royal Astronomical Society*, **226**, 601–627.
- Bruzual, G. & Charlot, S. (2003). Stellar Population Synthesis at the Resolution of 2003, *Monthly Notices of the Royal Astronomical Society*, **344**, 1000–1028.
- Burbidge, E. M., Burbidge, G. R., & Sandage, A. R. (1963). Evidence for the Occurrence of Violent Events in the Nuclei of Galaxies, *Reviews of Modern Physics*, **35**, 947–972.
- Burbidge, G. R. (1956). On Synchrotron Radiation from Messier 87, *Astrophysical Journal*, **124**, 416–429.
- Burbidge, G. R. (1959). Estimates of the Total Energy in Particles and Magnetic Field in the Non-Thermal Radio Sources, *Astrophysical Journal*, **129**, 849–851.
- Caffee, M. W., Reedy, R. C., Goswami, J. N., Hohenberg, C. M., & Marti, K. (1988). Irradiation records in meteorites, in *Meteorites and the Early Solar System*, eds Kerridge, J. & Matthews, M., pp. 205–245. Tuscon: University of Arizona Press.
- Calabretta, M. R. & Greisen, E. W. (2002). Representations of celestial coordinates in FITS, *Astronomy and Astrophysics*, **395**, 1077–1122.
- Camenzind, M. (2007). *Compact objects in astrophysics –white dwarfs, neutron stars and black holes*. Berlin: Springer-Verlag.
- Cameron, A. G. W. (1973). Abundances of the Elements in the Solar System, *Space Science Reviews*, **15**, 121–146.
- Cappelluti, N., Hasinger, G., Brusa, M., et al. (2007). The XMM-Newton wide-field survey in the COSMOS field II: X-ray data and the log N–log S, *ArXiv Astrophysics e-prints*.
- Carilli, C. L. & Barthel, P. D. (1996). Cygnus A, *Astronomy and Astrophysics Reviews*, **7**, 1–54.
- Carilli, C. L., Perley, R. A., Dreher, J. W., & Leahy, J. P. (1991). Multifrequency radio observations of Cygnus A - Spectral aging in powerful radio galaxies, *Astrophysical Journal*, **383**, 554–573.
- Carlstrom, J. E., Joy, M. K., Grego, L., et al. (2000). Imaging the Sunyaev-Zel’dovich Effect, in

- Particle Physics and the Universe: Proceedings of Nobel Symposium 198*, eds Bergström, L., Carlson, P., & and Fransson, C., pp. 148–155. Stockholm: Physica Scripta.
- Carron, N. (2007). *An introduction to the passage of energetic particles through matter*. : Taylor and Francis Group.
- Carter, B. (1971). Axisymmetric Black Hole Has Only Two Degrees of Freedom, *Physical Review Letters*, **26**, 331–333.
- Casandjian, J. & Grenier, I. A. (2008). A revised catalogue of EGRET  $\gamma$ -ray sources, *Astronomy and Astrophysics*, **489**, 849–883.
- Caswell, J. L. (1976). A map of the northern sky at 10 MHz, *Monthly Notices of the Royal Astronomical Society*, **177**, 601–616.
- Cavaliere, A. (1980). Models of X-ray Emission from Clusters of Galaxies, in *X-ray Astronomy*, eds Giacconi, R. & Setti, G., pp. 217–237. Dordrecht: D. Reidel Publishing Company.
- Cesarsky, C. J. (1980). Cosmic-ray confinement in the galaxy, *Annual Review of Astronomy and Astrophysics*, **18**, 289–319.
- Challinor, A. & Lasenby, A. (1998). Relativistic Corrections to the Sunyaev-Zeldovich Effect, *Astrophysical Journal*, **499**, 1–6.
- Chambers, K. C., Miley, G. K., & van Breugel, W. J. M. (1987). Alignment of Radio and Optical Orientations in High-Redshift Radio Galaxies, *Nature*, **329**, 604–606.
- Chandrasekhar, S. (1981). *Hydrodynamic and hydromagnetic stability*. New York: Dover Publications.
- Chandrasekhar, S. (1983). *The mathematical theory of black holes*. Oxford and New York: Clarendon Press/Oxford University Press.
- Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. (2000). Detection of Planetary Transits Across a Sun-like Star, *Astrophysical Journal*, **529**, L45–L48.
- Charlot, S. & Longhetti, M. (2001). Nebular Emission from Star-forming Galaxies, *Monthly Notices of the Royal Astronomical Society*, **323**, 887–903.
- Chevalier, R. A. (1998). Synchrotron Self-Absorption in Radio Supernovae, *Astrophysical Journal*, **499**, 810–819.
- Christensen-Dalsgaard, J. (2002). Helioseismology, *Reviews of Modern Physics*, **74**, 1073–1129.
- Christian, D. J. (2002). The Third Extreme Ultraviolet Explorer Right Angle Program Catalog: The Last Years, *Astronomical Journal*, **124**, 3478–3484.
- Chupp, E. L. (1976). *Gamma-ray astronomy: Nuclear transition region*. Dordrecht, D. Reidel Publishing Co.(Geophysics and Astrophysics Monographs. Volume 14).
- Chwolson, O. (1924). Über eine mögliche Form fiktiver Doppelsterne, *Astronomische Nachrichten*, **221**, 329–.
- Cimatti, A., Daddi, E., Renzini, A., et al. (2004). Old galaxies in the young Universe, *Nature*, **430**, 184–187.
- Clark, J. S., Goodwin, S. P., Crowther, P. A., et al. (2002). Physical parameters of the high-mass X-ray binary 4U1700-37, *Astronomy and Astrophysics*, **392**, 909–920.
- Clavel, J., Reichert, G. A., & 56 authors (1991). Steps toward Determination of the Size and Structure of the Broad-line Region in Active Galactic Nuclei. I – An 8 Month Campaign of Monitoring NGC 5548 with IUE, *Astrophysical Journal*, **366**, 64–81.
- Clemmow, P. C. W. & Dougherty, J. P. (1969). *Electrodynamics of Particles and Plasmas*. Reading, Massachusetts: Addison-Wesley Publishing Company.
- Coburn, W., Kretschmar, P., Kreykenbohm, I., et al. (2006). Cyclotron features in X-ray spectra of accreting pulsars, *Advances in Space Research*, **38**, 2747–2751.
- Cohen, M. H., Lister, M. L., Homan, D. C., et al. (2007). Relativistic Beaming and the Intrinsic Properties of Extragalactic Radio Jets, *Astrophysical Journal*, **658**, 232–244.
- Colless, M., Dalton, G., Maddox, S., et al. (2001). The 2dF Galaxy Redshift Survey: Spectra and Redshifts, *Monthly Notices of the Royal Astronomical Society*, **328**, 1039–1063.
- Colless, M. & Dunn, A. M. (1996). Structure and Dynamics of the Coma Cluster, *Astrophysical*

- Journal*, **458**, 435–454.
- Compton, A. H. (1923). The spectrum of scattered X-rays, *Physical Review*, **22**, 409–413.
- Condon, J. J. (1989). The 1.4 gigahertz luminosity function and its evolution, *Astrophysical Journal*, **338**, 13–23.
- Condon, J. J. (1992). Radio emission from normal galaxies, *Annual Review of Astronomy and Astrophysics*, **30**, 575–611.
- Cordes, J. M. & Lazio, T. J. W. (2002). NE2001.I. A New Model for the Galactic Distribution of Free Electrons and its Fluctuations, *ArXiv Astrophysics e-prints*.
- Cordes, J. M. & Lazio, T. J. W. (2003). NE2001. II. Using Radio Propagation Data to Construct a Model for the Galactic Distribution of Free Electrons, *ArXiv Astrophysics e-prints*.
- Costa, E., Frontera, F., Heise, J., et al. (1997). Discovery of an X-ray afterglow associated with the gamma-ray burst of 28 February 1997, *Nature*, **387**, 783–785.
- Cowie, L. (1988). Protogalaxies, in *The Post-Recombination Universe*, eds Kaiser, N. & Lasenby, A. N., pp. 1–18. Dordrecht: Kluwer Academic Publishers.
- Cowie, L., Lilly, S., Gardner, J., & McLean, I. (1988). A Cosmologically Significant Population of Galaxies Dominated by Very Young Star Formation, *Astrophysical Journal*, **332**, L29–L32.
- Cowie, L. L., Barger, A. J., & Kneib, J.-P. (2002). Faint Submillimeter Counts from Deep 850 Micron Observations of the Lensing Clusters A370, A851, and A2390, *Astronomical Journal*, **123**, 2197–2205.
- Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. D. (1996). New Insight on Galaxy Formation and Evolution From Keck Spectroscopy of the Hawaii Deep Fields, *Astronomical Journal*, **112**, 839–864.
- Cox, D. P. & Smith, B. W. (1974). Large-Scale Effects of Supernova Remnants on the Galaxy: Generation and Maintenance of a Hot Network of Tunnels, *Astrophysical Journal Letters*, **189**, L105–L108.
- Cristiani, S. (1986). Optical variability in quasars, in *Structure and evolution of active galactic nuclei*, eds Giuricin, G., Mardirossian, F., Mezzetti, M., & Ramella, M., pp. 83–91. Dordrecht: D. Reidel Publishing Company.
- Cruddace, R., Paresce, F., Bowyer, S., & Lampton, M. (1974). On the opacity of the interstellar medium to ultrasoft X-rays and extreme-ultraviolet radiation., *Astrophysical Journal*, **187**, 497–504.
- Dabrowski, Y., Fabian, A. C., Iwasawa, K., Lasenby, A. N., & Reynolds, C. S. (1997). The profile and equivalent width of the X-ray iron emission line from a disc around a Kerr black hole, *Monthly Notices of the Royal Astronomical Society*, **288**, L11–L15.
- Damon, P. E., Kaimei, D., Kocharov, G. E., Mikheeva, I. B., & Peristikh, A. N. (1995). Radiocarbon production by the gamma-ray component of supernova explosions, *Radiocarbon*, **37**, 599–604.
- Damon, P. E., Lerman, J. C., & Long, A. (1978). Temporal fluctuations of atmospheric  $^{14}\text{C}$ : causal factors and implications, *Annual Review of Earth and Planetary Science*, **6**, 457–494.
- Davidson, W. & Davies, M. (1964). Interpretation of the Counts of Radio Sources in Terms of a 4-parameter Family of Evolutionary Universes, *Monthly Notices of the Royal Astronomical Society*, **127**, 241–255.
- Davies, R. D. (2006). An anomalous dust emission component? - the observations, in *CMB and Physics of the Early Universe*, pp. 1–8. Proceedings of Science - on-line journal.
- Davis, L. & Greenstein, J. L. (1951). The Polarization of Starlight by Aligned Dust Grains, *Astrophysical Journal*, **114**, 206–240.
- de Plaa, J., Kaastra, J. S., Méndez, M., et al. (2005). The temperature structure in the core of Sésic 159-03, *Advances in Space Research*, **36**, 601–604.
- de Vaucouleurs, G., de Vaucouleurs, A., Corwin Jr., H. G., et al. (1991). *Third Reference Catalogue of Bright Galaxies: Containing Information on 23,024 Galaxies With Reference to Papers Published Between 1913 and 1988*. Berlin: Springer-Verlag.

- Dermer, C. D. (1986). Secondary production of neutral pi-mesons and the diffuse galactic gamma radiation, *Astronomy and Astrophysics*, **157**, 223–229.
- Deubner, F.-L. & Gough, D. (1984). Helioseismology: Oscillations as a Diagnostic of the Solar Interior, *Annual Review of Astronomy and Astrophysics*, **22**, 593–619.
- Dey, A. (1997). The Host Galaxies of Distant Radio Sources, in *The Hubble Space Telescope and the High Redshift Universe*, eds Tanvir, N. R., Aragón-Salamanca, A., & Wall, J. V., pp. 373–376. Singapore: World Scientific Publishing Company.
- Diehl, R., Halloin, H., Kretschmer, K., et al. (2006a). Radioactive  $^{26}\text{Al}$  from massive stars in the Galaxy, *Nature*, **439**, 45–47.
- Diehl, R., Prantzos, N., & von Ballmoos, P. (2006b). Astrophysical constraints from gamma-ray spectroscopy, *Nuclear Physics A*, **777**, 70–97.
- Dirac, P. (1928a). The Quantum Theory of the Electron, *Proceedings of the Royal Society of London*, **A117**, 610–624.
- Dirac, P. (1928b). The Quantum Theory of the Electron II, *Proceedings of the Royal Society of London*, **A118**, 351–361.
- Djorgovski, S. G. & Davis, M. (1987). Fundamental Properties of Elliptical Galaxies, *Astrophysical Journal*, **313**, 59–68.
- Doeleman, S. S., Weintraub, J., Rogers, A. E. E., et al. (2008). Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre, *Nature*, **455**, 78–80.
- Dombrovski, V. A. (1954). On the Nature of the Radiation from the Crab Nebula, *Doklady Akademiiy Nauk SSSR*, **94**, 1021–1024.
- Dopita, M. A. & Sutherland, R. S. (1996). Spectral Signatures of Fast Shocks. I. Low-Density Model Grid, *Astrophysical Journal Supplement*, **102**, 161–188.
- Draine, B. T. (2003). Interstellar Dust Grains, *Annual Reviews of Astronomy and Astrophysics*, **41**, 241–289.
- Draine, B. T. (2004). Astrophysics of dust in cold clouds, in *The Cold Universe, Saas-Fee Advanced Course 32*, eds Blain, A. W., Combes, F., Draine, B. T., Pfenniger, D., & Revaz, Y., pp. 213–XXX. Berlin: Springer-Verlag.
- Draine, B. T. & Lazarian, A. (1998). Electric dipole radiation from spinning dust grains, *Astrophysical Journal*, **508**, 157–179.
- Dreher, J. W., Carilli, C. L., & Perley, R. A. (1987). The Faraday rotation of Cygnus A - Magnetic fields in cluster gas, *Astrophysical Journal*, **316**, 611–625.
- Dressler, A. (1980). Galaxy Morphology in Rich Clusters – Implications for the Formation and Evolution of Galaxies, *Astrophysical Journal*, **236**, 351–365.
- Dressler, A., Lynden-Bell, D., Burstein, D., et al. (1987). Spectroscopy and Photometry of Elliptical Galaxies. I – A New Distance Estimator, *Astrophysical Journal*, **313**, 42–58.
- Driver, S. P., Allen, P. D., Graham, A. W., et al. (2006). The Millennium Galaxy Catalogue: Morphological Classification and Bimodality in the Colour-Concentration Plane, *Monthly Notices of the Royal Astronomical Society*, **368**, 414–434.
- Drury, L. O., Duffy, P., Eichler, D., & Mastichiadis, A. (1999). On “box” models of shock acceleration and electron synchrotron spectra, *Astronomy and Astrophysics*, **347**, 370–374.
- Drury, L. O. & Falle, S. A. E. G. (1986). On the Stability of Shocks Modified by Particle Acceleration, *Monthly Notices of the Royal Astronomical Society*, **223**, 353–376.
- Dunlop, J. S. (1998). Cosmic Star-Formation and Radio Source Evolution, in *ASSL Vol. 226: Observational Cosmology with the New Radio Surveys*, eds Bremer, M. N., Jackson, N., & Perez-Fournon, I., pp. 157–164.
- Dunlop, J. S. & Peacock, J. A. (1990). The Redshift Cut-off in the Luminosity Function of Radio Galaxies and Quasars, *Monthly Notices of the Royal Astronomical Society*, **247**, 19–42.
- Dunlop, J. S., Peacock, J. A., Spinrad, H., et al. (1996). A 3.5-Gyr-old Galaxy at Redshift 1.55, *Nature*, **381**, 581–584.
- Edelson, R., Vaughan, S., Warwick, R., Puchnarewicz, E., & George, I. (1999). The ROSAT Wide



- Field Camera Extragalactic Survey, *Monthly Notices of the Royal Astronomical Society*, **307**, 91–98.
- Efstathiou, G. (1990). Cosmological Perturbations, in *Physics of the Early Universe*, eds Peacock, J. A., Heavens, A. F., & Davies, A. T., pp. 361–463. Edinburgh: SUSSP Publications.
- Eguchi, K., Enomoto, S., & 97 authors (2003). First Results from Kamland: Evidence for Reactor Anti-neutrino Disappearance, *Physical Review Letters*, **90**, id. 021802(1–6).
- Einstein, A. (1905). Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt, *Annalen der Physik*, **322**, 132–148.
- Einstein, A. (1915). Die Feldgleichung der Gravitation (The Field Equations of Gravitation), *Sitzungsberichte, Königlich Preussische Akademie der Wissenschaften (Berlin)*, **II**, 844–847.
- Einstein, A. (1936). Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field, *Science*, **84**, 506–507.
- Ellis, G. R. A. (1982). Galactic radio emission below 16.5 MHz and the galactic emission measure, *Australian Journal of Physics*, **35**, 91–104.
- Ellis, R. G. (1997). Faint Blue Galaxies, *Annual Review of Astronomy and Astrophysics*, **35**, 389–443.
- Ellis, S. C. & Bland-Hawthorn, J. (2006). GalaxyCount: a JAVA calculator of galaxy counts and variances in multiband wide-field surveys to 28 AB mag, *ArXiv Astrophysics e-prints*.
- Enge, H. A. (1966). *Introduction to nuclear physics*. London: Addison-Wesley.
- Erber, T. (1966). High-Energy Electromagnetic Conversion Processes in Intense Magnetic Fields, *Reviews of modern physics*, **38**, 626–659.
- Eugster, O., Herzog, G. F., Marti, K., & Caffee, M. W. (2006). *Irradiation Records, Cosmic-Ray Exposure Ages, and Transfer Times of Meteorites*, pp. 829–851. Meteorites and the Early Solar System II.
- Fabbiano, G., Trinchieri, G., Elvis, M., Miller, L., & Longair, M. (1984). An X-ray survey of a complete sample of 3CR radio galaxies, *Astrophysical Journal*, **277**, 115–131.
- Faber, S. M. (1973). Variations in Spectral-Energy Distributions and Absorption-Line Strengths among Elliptical Galaxies, *Astrophysical Journal*, **179**, 731–754.
- Faber, S. M. (1999). Black holes in galaxy centers, in *Formation of Structure in the Universe*, eds A. Dekel, A. & Ostriker, J. P., pp. 337–359.
- Faber, S. M. & Jackson, R. E. (1976). Velocity Dispersions and Mass-to-light Ratios for Elliptical Galaxies, *Astrophysical Journal*, **204**, 668–683.
- Fabian, A. C. (1994). Cooling Flows in Clusters of Galaxies, *Annual Review of Astronomy and Astrophysics*, **32**, 277–318.
- Fabian, A. C. (1998). Emission lines: signatures of relativistic rotation, in *Theory of Black Hole Accretion Disks*, eds Abramowicz, M. A., Björnsson, G., & Pringle, J. E., pp. 123–133. Cambridge: Cambridge University Press.
- Fabian, A. C. (2009). Black holes at work, *Astronomy and Geophysics*, **30**, 3.18–3.24.
- Fabian, A. C. & Rees, M. J. (1995). The accretion luminosity of a massive black hole in an elliptical galaxy, *Monthly Notices of the Royal Astronomical Society*, **277**, L55–L58.
- Fabian, A. C., Sanders, J. S., Ettori, S., et al. (2000). Chandra Imaging of the Complex X-ray Core of the Perseus Cluster, *Monthly Notices of the Royal Astronomical Society*, **318**, L65–L68.
- Fabian, A. C., Sanders, J. S., Taylor, G. B., et al. (2006). A Very Deep Chandra Observation of the Perseus Cluster: Shocks, Ripples and Conduction, *Monthly Notices of the Royal Astronomical Society*, **366**, 417–428.
- Fabian, A. C., Vaughan, S., Nandra, K., et al. (2002). A long hard look at MCG-6-30-15 with XMM-Newton, *Monthly Notices of the Royal Astronomical Society*, **335**, L1–L5.
- Fabricant, D. G., Lecar, M., & Gorenstein, P. (1980). X-ray Measurements of the Mass of M87, *Astrophysical Journal*, **241**, 552–560.
- Fan, X., Hennawi, J. F., Richards, G. T., et al. (2004). A Survey of  $z \geq 5.7$  Quasars in the Sloan Digital Sky Survey. III. Discovery of Five Additional Quasars, *Astronomical Journal*, **128**,

- 515–522.
- Fan, X., Narayanan, V. K., Lupton, R. H., et al. (2001). A Survey of  $z \geq 5.8$  Quasars in the Sloan Digital Sky Survey. I. Discovery of Three New Quasars and the Spatial Density of Luminous Quasars at  $z \sim 6$ , *Astronomical Journal*, **122**, 2833–2849.
- Fanaroff, B. L. & Riley, J. M. (1974). The Morphology of Extragalactic Radio Sources of High and Low Luminosity, *Monthly Notices of the Royal Astronomical Society*, **167**, 31P–36P.
- Felten, J. (1977). Study of the Luminosity Function for Field Galaxies, *Astronomical Journal*, **82**, 861–878.
- Fermi, E. (1949). On the Origin of the Cosmic Radiation, *Physical Review*, **75**, 1169–1174.
- Fernini, I., Burns, J. O., Leahy, J. P., & Basart, J. P. (1991). Depolarization asymmetry in the quasar 3C 47, *Astrophysical Journal*, **381**, 63–71.
- Ferrario, D. T., Wickramasinghe, D. T., Bailey, I. R., Tuohy, I. R., & Hough, J. H. (1989). EXO 033319-2554.2: an eclipsing AM Herculis system showing cyclotron emission features, *Astrophysical Journal*, **337**, 832–842.
- Feynman, R., Leighton, R. B., & Sands, M. L. (1965). *Feynman Lectures on Physics*. Redwood City, California: Addison-Wesley Publishing Company.
- Feynman, R. P. (1972). *Statistical Mechanics: A Set of Lectures*. Reading, Massachusetts: W. A. Benjamin.
- Fich, M. & Tremaine, S. (1991). The mass of the Galaxy, *Annual Review of Astronomy and Astrophysics*, **29**, 409–445.
- Field, G. B. (1965). Thermal Instability, *Astrophysical Journal*, **142**, 531–567.
- Field, G. B., Goldsmith, D. W., & Habing, H. J. (1969). Cosmic-Ray Heating of the Interstellar Gas, *Astrophysical Journal Letters*, **55**, L149–L154.
- Fitch, W. S., Pacholczyk, A. G., & Weymann, R. J. (1967). Light Variations of the Seyfert Galaxy NGC 4151, *Astrophysical Journal*, **150**, L67–L70.
- Fitzpatrick, R. (2008). *The Physics of Plasmas*. Lulu publishers. available at: <http://farside.ph.utexas.edu/teaching/plasma/380.pdf>.
- Ford, H. C., Harms, R. J., Tsvetanov, Z. I., et al. (1994). Narrowband HST Images of M87: Evidence for a Disk of Ionized Gas around a Massive Black Hole, *Astrophysical Journal Letters*, **435**, L27–L30.
- Forman, W., Jones, C., Cominsky, L., et al. (1978). The fourth UHURU catalog of X-ray sources, *Astrophysical Journal Supplement Series*, **38**, 357–412.
- Fort, B. & Mellier, Y. (1994). Arc(let)s in clusters of galaxies., *Astronomy and Astrophysics Reviews*, **5**, 239–292.
- Francis, P. J., Hewett, P. C., Foltz, C. B., et al. (1991). A high signal-to-noise ratio composite quasar spectrum, *Astrophysical Journal*, **373**, 465–470.
- Frank, J., King, A., & Raine, D. J. (2002). *Accretion Power in Astrophysics: Third Edition*. Cambridge: Cambridge University Press.
- Frank, J., King, A. R., & Lasota, J.-P. (1987). The light curves of low-mass X-ray binaries, *Astronomy and Astrophysics*, **178**, 137–142.
- Frolov, V. P. & Novikov, I. D. (1998). *Black hole physics : basic concepts and new developments*. Dordrecht: Kluwer Academic Publishing Company.
- Fukuda, S., Fukuda, Y., & 117 authors (2001). Solar  $^8\text{B}$  and hep Neutrino Measurements from 1258 Days of Super-Kamiokande Data, *Physical Review Letters*, **86**, 5651–5655.
- Galama, T. J., Vreeswijk, P. M., van Paradijs, J., et al. (1998). An unusual supernova in the error box of the  $\gamma$ -ray burst of 25 April 1998, *Nature*, **395**, 670–672.
- Garcia-Munoz, M., Simpson, J. A., Guzik, T. G., Wefel, J. P., & Margolis, S. H. (1987). Cosmic-ray propagation in the Galaxy and in the heliosphere - The path-length distribution at low energy, *Astrophysical Journal Supplement*, **64**, 269–304.
- Garrington, S. T., Leahy, J. P., Conway, R. G., & Laing, R. A. (1988). A systematic asymmetry in the polarization properties of double radio sources with one jet, *Nature*, **331**, 147–149.

- Gavazzi, R., Treu, T., Rhodes, J. D., et al. (2007). The Sloan Lens ACS Survey. IV: the mass density profile of early-type galaxies out to 100 effective radii, *Astrophysical Journal*, **667**, 176–190.
- Gehrels, N., Ramirez-Ruiz, E., & Fox, D. B. (2009). Gamma-Ray Bursts in the Swift Era, *Annual Review of Astronomy and Astrophysics*, **47**, 567–617.
- Geiger, H. & Müller, W. (1928). Das Electronenzählrohr (The Electron-Counting Tube), *Physicalische Zeitschrift*, **29**, 839–841.
- Geiger, H. & Müller, W. (1929). Technische Bemerkungen zum Electronenzählrohr (Technical Remarks on the Electron Counting Tube), *Physicalische Zeitschrift*, **30**, 489–493.
- Genzel, R., Schödel, R., Ott, T., et al. (2003). Near-infrared Flares from Accreting Gas around the Supermassive Black hole at the Galactic Centre, *Nature*, **425**, 934–937.
- Ghez, A. M., Morris, M., Becklin, E. E., Tanner, A., & Kremenek, T. (2000). The Accelerations of Stars Orbiting the Milky Way's Central Black Hole, *Nature*, **407**, 349–351.
- Giacalone, J. & Jokipii, J. R. (2007). Magnetic Field Amplification by Shocks in Turbulent Fluids, *Astrophysical Journal Letters*, **663**, L41–L44.
- Giacconi, R., Gursky, H., Kellogg, E., Schreier, E., & Tananbaum, H. (1971). Discovery of Periodic X-Ray Pulsations in Centaurus X-3 from UHURU, *Astrophysical Journal*, **167**, L67–L73.
- Giacconi, R., Gursky, H., & van Speybroeck, L. P. (1968). Observational Techniques in X-Ray Astronomy, *Annual Review of Astronomy and Astrophysics*, **6**, 373–416.
- Giavalisco, M., Dickinson, M., Ferguson, H. C., et al. (2004). The Rest-Frame Ultraviolet Luminosity Density of Star-forming Galaxies at Redshifts  $z \geq 3.5$ , *Astrophysical Journal Letters*, **600**, L103–L106.
- Gilli, R., Comastri, A., & Hasinger, G. (2007). The synthesis of the cosmic X-ray background in the Chandra and XMM-Newton era, *Astronomy and Astrophysics*, **463**, 79–96.
- Ginzburg, V. L. (1951). Cosmic Rays as a Source of Galactic Radio-radiation, *Doklady Akademiiy Nauk SSSR*, **76**, 377–380.
- Ginzburg, V. L., Sazonov, V. N., & Syrovatskii, S. I. (1968). Synchrotron Radiation and its Reabsorption, *Soviet Physics Uspekhi*, **11**, 34–41.
- Ginzburg, V. L. & Syrovatskii, S. I. (1964). *The origin of cosmic rays*. Oxford: Pergamon Press.
- Ginzburg, V. L. & Syrovatskii, S. I. (1965). Cosmic magnetobremstrahlung (synchrotron radiation), *Annual Review of Astronomy and Astrophysics*, **3**, 297–350.
- Ginzburg, V. L. & Syrovatskii, S. I. (1969). Developments in the Theory of Synchrotron Radiation and its Reabsorption, *Annual Review of Astronomy and Astrophysics*, **7**, 375–420.
- Glazebrook, K., Abraham, R. G., McCarthy, P. J., et al. (2004). A High Abundance of Massive Galaxies 3–6 Billion Years after the Big Bang, *Nature*, **430**, 181–184.
- Glazebrook, K., Ellis, R. S., Colless, M., et al. (1995). The Morphological Identification of the Rapidly Evolving Population of Faint Galaxies, *Monthly Notices of the Royal Astronomical Society*, **275**, L19–L22.
- Gold, T. (1968). Rotating Neutron Stars as the Origin of Pulsating Radio Sources, *Nature*, **218**, 731–732.
- Goldreich, P. & Julian, W. H. (1969). Pulsar Electrodynamics, *Astrophysical Journal*, **157**, 869–880.
- Goodrich, R. W. & Osterbrock, D. E. (1983). MRK 744 and MRK 1066 - Two Seyfert galaxies with strong absorption-line spectra, *Astrophysical Journal*, **269**, 416–422.
- Gould, R. J. (2005). *Electromagnetic Processes*. Princeton: Princeton University Press.
- Gradshteyn, I. S. & Ryzhik, I. M. (1980). *Tables of integrals, series and products*. New York: Dover Publications.
- Granot, J. (2008). Critical Review of Basic Afterglow Concepts, *ArXiv e-prints*.
- Granot, J. & Sari, R. (2002). The Shape of Spectral Breaks in Gamma-Ray Burst Afterglows, *Astrophysical Journal*, **568**, 820–829.
- Green, D. A., Reynolds, S. P., Borkowski, K. J., et al. (2008). The radio expansion and brightening of the very young supernova remnant G1.9+0.3, *Monthly Notices of the Royal Astronomical Society*, **387**, L54–L58.



- Greenhill, L. J., Henkel, C., Becker, R., Wilson, T. L., & Wouterloot, J. G. A. (1995a). Centripetal acceleration within the subparsec nuclear maser disk of NGC 4258., *Astronomy and Astrophysics*, **304**, 21–33.
- Greenhill, L. J., Jiang, D. R., Moran, J. M., et al. (1995b). Detection of a Subparsec Diameter Disk in the Nucleus of NGC 4258, *Astrophysical Journal*, **440**, 619–627.
- Greiner, J., Cuby, J. G., & McCaughrean, M. J. (2001). An unusually massive stellar black hole in the Galaxy, *Nature*, **414**, 522–525.
- Greisen, K. (1966). End to the Cosmic-Ray Spectrum?, *Physical Review Letters*, **16**, 748–750.
- Griffin, R. F. (1985). The distributions of periods and amplitudes of late-type spectroscopic binaries, in *Interacting Binaries*, eds Eggleton, P. P. & Pringle, J. E., pp. 1–12.
- Gueth, F. & Guilleloteau, S. (1999). The jet-driven molecular outflow of HH 211, *Astronomy and Astrophysics*, **343**, 571–584.
- Gugliucci, N. E., Taylor, G. B., Peck, A. B., & Giroletti, M. (2005). Dating COINS: kinematic ages for compact symmetric objects, *Astrophysical Journal*, **622**, 136–148.
- Gull, S. F. (1975). The X-ray, Optical and Radio Properties of Young Supernova Remnants, *Monthly Notices of the Royal Astronomical Society*, **171**, 263–278.
- Gull, S. F. & Northover, K. J. E. (1973). Bubble Model of Extragalactic Radio Sources, *Nature*, **244**, 80–83.
- Gunn, J. E. (1978). The Friedmann Models and Optical Observations in Cosmology, in *Observational Cosmology: 8th Advanced Course, Swiss Society of Astronomy and Astrophysics, Saas-Fee 1978*, eds Maeder, A., Martinet, L., & Tammann, G., pp. 1–121. Geneva: Geneva Observatory Publications.
- Gunn, J. E. & Ostriker, J. P. (1970). On the nature of pulsars. III. Analysis of observations, *Astrophysical Journal*, **160**, 979–.
- Haberl, F. (2007). The magnificent seven: magnetic fields and surface temperature distributions, *Astrophysics and Space Science*, **308**, 181–190.
- Hague, J. D. (2009). Correlation of the highest energy cosmic rays with nearby extragalactic objects in Pierre Auger Observatory data, in *Proceedings of the 31st International Cosmic Ray Conference (Lodz, Poland)*, ed. XX, pp. XX–XX. XX.
- Hampel, W., Handt, J., Heusser, G., et al. (1999). GALLEX Solar Neutrino Observations: Results for GALLEX IV, *Physics Letters B*, **447**, 127–133.
- Häring, N. & Rix, H. (2004). On the Black Hole Mass-Bulge Mass Relation, *Astrophysical Journal Letters*, **604**, L89–L92.
- Harms, R. J., Ford, H. C., Tsvetanov, Z. I., et al. (1994). HST FOS Spectroscopy of M87: Evidence for a Disk of Ionized Gas around a Massive Black Hole, *Astrophysical Journal Letters*, **435**, L35–L38.
- Hasinger, G., Burg, R., Giacconi, R., et al. (1993). A Deep X-ray Survey in the Lockman Hole and the soft X-ray Log  $N$ –Log  $S$ , *Astronomy and Astrophysics*, **275**, 1–15.
- Hasinger, G. & van der Klis, M. (1989). Two patterns of correlated X-ray timing and spectral behaviour in low-mass X-ray binaries, *Astronomy and Astrophysics*, **225**, 79–96.
- Hauser, M. G., Arendt, R. G., Kelsall, T., et al. (1998). The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. I. Limits and Detections, *Astrophysical Journal*, **508**, 25–43.
- Hauser, M. G. & Dwek, E. (2001). The Cosmic Infrared Background: Measurements and Implications, *Annual Review of Astronomy and Astrophysics*, **39**, 249–307.
- Hawking, S. W. (1972). Black Holes in General Relativity, *Communications in Mathematical Physics*, **25**, 152–166.
- Hawking, S. W. (1975). Particle Creation by Black Holes, in *Quantum gravity; Proceedings of the Oxford Symposium*, eds Isham, C. J., Penrose, R., & Sciama, D. W., pp. 219–267. Oxford: Clarendon Press.
- Hawking, S. W. & Ellis, G. R. (1973). *The Large Scale Structure of Space-Time*. Cambridge:

Cambridge University Press.

- Hawkins, M. R. S. (1986). On the nature of objects detected as faint long-term variables, *Monthly Notices of the Royal Astronomical Society*, **219**, 417–426.
- Hayashi, C. (1961). Stellar Evolution in Early Phases of Gravitational Contraction, *Publications of the Astronomical Society of Japan*, **13**, 450–452.
- Hazard, C., Mackey, M. B., & Shimmins, A. J. (1963). Investigation of the Radio Source 3C 273 by the Method of Lunar Occultations, *Nature*, **197**, 1037–1039.
- Heckman, T. M. (1980). An optical and radio survey of the nuclei of bright galaxies - Activity in normal galactic nuclei, *Astronomy and Astrophysics*, **87**, 152–164.
- Heiles, C. (1976). The interstellar magnetic field, *Annual Review of Astronomy and Astrophysics*, **14**, 1–22.
- Heitler, W. (1954). *The Quantum Theory of Radiation*. Oxford: Oxford University Press.
- Hess, V. (1912). Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten, (Concerning Observations of Penetrating Radiation on Seven Free Balloon Flights), *Physikalische Zeitschrift*, **13**, 1084–1091.
- Hesser, J. E., Harris, W. E., VandenBerg, D. A., et al. (1987). A CCD Color-magnitude Study of 47 Tucanae, *Publications of the Astronomical Society of the Pacific*, **99**, 739–808.
- Hewish, A. (1986). The pulsar era, *Quarterly Journal of the Royal Astronomical Society*, **27**, 548–558.
- Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., & Collins, R. A. (1968). Observations of a Rapidly Pulsating Radio Source, *Nature*, **217**, 709–713.
- Hewitt, J. N., Turner, E. L., Burke, B. F., Lawrence, C. R., & Bennett, C. L. (1987). A VLA gravitational lens survey, in *Observational Cosmology: IAU Symposium No. 124*, eds Hewitt, A., Burbidge, G., & Fang, L. Z., pp. 747–750. Dordrecht: D. Reidel Publishing Company.
- Heyvaerts, J. (1981). Particle acceleration in solar flares., in *Solar flare magnetohydrodynamics*, ed. Priest, E. R., pp. 429–555. London: Gordon and Breach.
- Hildebrand, R. H. (1983). The Determination of Cloud Masses and Dust Characteristics from Submillimetre Thermal Emission, *Quarterly Journal of the Royal Astronomical Society*, **24**, 267–282.
- Hillas, A. M. (1984). The Origin of Ultra-High-Energy Cosmic Rays, *Annual Review of Astronomy and Astrophysics*, **22**, 425–444.
- Hillebrandt, W. & Niemeyer, J. C. (2000). Type IA Supernova Explosion Models, *Annual Review of Astronomy and Astrophysics*, **38**, 191–230.
- Hillenbrand, L. A. (1997). On the Stellar Population and Star-Forming History of the Orion Nebula Cluster, *Astronomical Journal*, **113**, 1733–1768.
- Hinton, J. (2009). Ground-based gamma-ray astronomy with Cherenkov telescopes, *New Journal of Physics*, **11**(5), 055005–+.
- Hirata, K. S., Inoue, K., Kajita, T., Kifune, T., & Kihara, K. (1990). Results from One Thousand Days of Real-time, Directional Solar-Neutrino Data, *Physical Review Letters*, **65**, 1297–1300.
- Hjellming, R. M. & Johnston, K. J. (1981). An analysis of the proper motions of SS 433 radio jets, *Astrophysical Journal Letters*, **246**, L141–L145.
- Hjorth, J., Sollerman, J., Møller, P., et al. (2003). A Very Energetic Supernova Associated with the  $\gamma$ -ray burst of 29 March 2003, *Nature*, **423**, 847–850.
- Hoekstra, H., Yee, H. K. C., & Gladders, M. D. (2004). Properties of Galaxy Dark Matter Halos from Weak Lensing, *Astrophysical Journal*, **606**, 67–77.
- Hogg, D. W., Blanton, M. R., Brinchmann, J., et al. (2004). The Dependence on Environment of the Color-Magnitude Relation of Galaxies, *Astrophysical Journal*, **601**, L29–L32.
- Holloway, N. J. & Pryce, M. H. L. (1981). Properties of gaps in pulsar magnetospheres, *Monthly Notices of the Royal Astronomical Society*, **194**, 95–110.
- Homan, D. C., Kadler, M., Kellermann, K. I., et al. (2009). MOJAVE: Monitoring of Jets in Active Galactic Nuclei with VLBA Experiments. VII. Blazar Jet Acceleration, *Astrophysical Journal*,

- 706, 1253–1268.
- Hook, I. M., McMahon, R. G., Boyle, B. J., & Irwin, M. J. (1991). The variability of a large sample of quasars, in *The Space Distribution of Quasars*, ed. Crampton, D., volume 21, pp. 67–75. San Francisco: Astronomical Society of the Pacific Conference Series.
- Horne, K. & Marsh, T. R. (1986). Indirect Imaging of Accretion Disks in Binaries, in *The Physics of Accretion onto Compact Objects*, eds Mason, K. O., Watson, M. G., & White, N. E., pp. 1–13. Berlin: Springer Verlag.
- Hosaka, J., Ishihara, K., Kameda, J., et al. (2006). Solar neutrino measurements in Super-Kamiokande-I, *Physical Review D*, **73**, 112001–+.
- Hoyle, F. & Fowler, W. A. (1963). On the Nature of Strong Radio Sources, *Monthly Notices of the Royal Astronomical Society*, **125**, 169–176. Also, Nature of Strong Radio Sources, (1963), *Nature*, **197**, 533–535.
- Hoyle, F. & Lyttleton, R. A. (1939). The effect of interstellar matter on climatic variation, *Proceedings of the Cambridge Philosophical Society*, **35**, 405–XXX.
- Hubble, E. P. (1929). A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae, *Proceedings of the National Academy of Sciences*, **15**, 168–173.
- Hubble, E. P. (1936). *The Realm of the Nebulae*. New Haven: Yale University Press.
- Huchra, J., Jarrett, T., Skrutskie, M., et al. (2005). The 2MASS Redshift Survey and Low Galactic Latitude Large-Scale Structure, in *Nearby Large-Scale Structures and the Zone of Avoidance*, ed. Woudt, A. P. F. . P. A., volume 329 of *Astronomical Society of the Pacific Conference Series*, pp. 135–146.
- Hughes, P. A. (1991). *Beams and jets in astrophysics*.
- Hulse, R. A. & Taylor, J. H. (1975). Discovery of a Pulsar in a Binary System, *Astrophysical Journal Letters*, **195**, L51–L53.
- Illingworth, G. (1977). Rotation (?) in 13 Elliptical Galaxies, *Astrophysical Journal Letters*, **218**, L43–L47.
- Inskip, K. J., Best, P. N., Longair, M. S., & MacKay, D. J. C. (2002). Infrared Magnitude-redshift Relations for Luminous Radio Galaxies, *Monthly Notices of the Royal Astronomical Society*, **329**, 277–289.
- Irwin, M., McMahon, R. G., & Hazard, C. (1991). APM optical surveys for high redshift quasars, in *ASP Conf. Ser. 21: The Space Distribution of Quasars*, ed. Crampton, D., pp. 117–126.
- Iyudin, A. F., Diehl, R., Bloemen, H., et al. (1994). COMPTEL observations of Ti-44 gamma-ray line emission from CAS A, *Astronomy and Astrophysics*, **284**, L1–L4.
- Jackson, J. D. (1999). *Classical Electrodynamics*. New York: John Wiley and Sons.
- Jenkins, E. B. (1987). Observations of absorption lines from highly ionized atoms, in *Exploring the Universe with the IUE Satellite*, ed. Kondo, Y., volume 129 of *Astrophysics and Space Science Library*, pp. 531–548.
- Jennison, R. C. & Das Gupta, M. K. (1953). Fine Structure of the Extra-Terrestrial Radio Source Cygnus 1, *Nature*, **172**, 996–997.
- Jokipii, J. R. (1973). Turbulence and scintillations in the interplanetary plasma, *Annual Review of Astronomy and Astrophysics*, **11**, 1–28.
- Kaastra, J. S., Tamura, T., Peterson, J. R., et al. (2004). Spatially Resolved X-ray Spectroscopy of Cooling Clusters of Galaxies, *Astronomy and Astrophysics*, **413**, 415–439.
- Kaiser, C. R. & Alexander, P. (1997). A self-similar model for extragalactic radio sources, *Monthly Notices of the Royal Astronomical Society*, **286**, 215–222.
- Kaler, J. (2001). Planetary Nebulae, *Encyclopedia of Astronomy and Astrophysics*, **3**, 2066–2074.
- Kang, H. & Jones, T. W. (2006). Numerical studies of diffusive shock acceleration at spherical shocks, *Astroparticle Physics*, **25**, 246–258.
- Kang, H., Ryu, D., & Jones, T. W. (2009). Self-Similar Evolution of Cosmic-Ray Modified Shocks: The Cosmic-Ray Spectrum, *Astrophysical Journal*, **695**, 1273–1288.
- Kapahi, V. K. & Saikia, D. J. (1982). Relativistic beaming in the central components of double

- radio quasars, *Journal of Astrophysics and Astronomy*, **3**, 465–483.
- Karttunen, H., Kroger, P., Oja, H., Poutanen, M., & Donner, K. (2007). *Fundamental Astronomy*. Heidelberg: Springer-Verlag.
- Karzas, W. J. & Latter, R. (1961). Electron Radiative Transitions in a Coulomb Field., *Astrophysical Journal Supplement*, pp. 167–212.
- Katz-Stone, D. M., Kassim, N. E., Lazio, T. J. W., & O'Donnell, R. (2000). Spatial Variations of the Synchrotron Spectrum within Tycho's Supernova Remnant (3C 10): A Spectral Tomography Analysis of Radio Observations at 20 and 90 Centimeter Wavelengths, *Astrophysical Journal*, **529**, 453–462.
- Kauffmann, G., Heckman, T. M., White, S. D. M., et al. (2003). The Dependence of Star Formation History and Internal Structure on Stellar Mass for  $10^5$  low-redshift Galaxies, *Monthly Notices of the Royal Astronomical Society*, **341**, 54–69.
- Kellermann, K. I., Vermeulen, R. C., Zensus, J. A., & Cohen, M. H. (1998). Sub-Milliarcsecond Imaging of Quasars and Active Galactic Nuclei, *Astronomical Journal*, **115**, 1295–1318.
- Kembhavi, A., Feigelson, E. D., & Singh, K. P. (1986). X-ray and radio core emission in radio quasars, *Monthly Notices of the Royal Astronomical Society*, **220**, 51–67.
- Kembhavi, A. K. & Narlikar, J. V. (1999). *Quasars and active galactic nuclei – an introduction*. Cambridge: Cambridge University Press.
- Kennicutt, R. (1989). The Star Formation Law in Galactic Discs, *Astrophysical Journal*, **344**, 685–703.
- Kennicutt, R. (2006). Young Spirals Get Older, *Nature*, **442**, 753–754.
- Kennicutt, R. C., Edgar, B. K., & Hodge, P. W. (1989). Properties of H II Region Populations in Galaxies. II - The H II Region Luminosity Function, *Astrophysical Journal*, **337**, 761–781.
- Kennicutt, Jr., R. C. (1998). The Global Schmidt Law in Star-forming Galaxies, *Astrophysical Journal*, **498**, 541–552.
- Kent, S. M. & Gunn, J. E. (1982). The Dynamics of Rich Clusters of Galaxies. I - The Coma Cluster, *Astronomical Journal*, **87**, 945–971.
- Kerr, R. P. (1963). Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics, *Physical Review Letters*, **11**, 237–238.
- Khachikian, E. Y. & Weedman, D. W. (1971). A Spectroscopic Study of Luminous Galactic Nuclei, *Astrofizika*, **7**, 389–406.
- Khachikian, E. Y. & Weedman, D. W. (1974). An Atlas of Seyfert Galaxies, *Astrophysical Journal*, **192**, 581–589.
- Kiepenheuer, K. O. (1950). Cosmic Rays as the Source of General Galactic Radio Emission, *Physical Review*, **79**, 738–739.
- King, I. R. (1966). The Structure of Star Clusters. III. Some Simple Dynamical Models, *Astronomical Journal*, **71**, 64–75.
- King, I. R. (1981). The Dynamics of Globular Clusters, *Quarterly Journal of the Royal Astronomical Society*, **22**, 227–243.
- Kippenhahn, R. & Weigert, A. (1990). *Stellar Structure and Evolution*. Berlin and Heidelberg: Springer-Verlag.
- Klebesadel, R. W., Strong, I. B., & Olson, R. A. (1973). Observations of Gamma-Ray Bursts of Cosmic Origin, *Astrophysical Journal Letters*, **182**, L85–L88.
- Klochkov, D., Staubert, R., Postnov, K., et al. (2008). INTEGRAL observations of Hercules X-1, *Astronomy and Astrophysics*, **482**, 907–915.
- Kneib, J. P. (1993). *Ph.D Dissertation*. Universit Paul Sabatier, Toulouse.
- Koch, H. W. & Motz, J. W. (1959). Bremsstrahlung cross-section formulas and related data, *Reviews of modern physics*, **31**, 920–955.
- Kolb, E. W. & Turner, M. S. (1990). *The Early Universe*. Redwood City, California: Addison-Wesley Publishing Co.
- Kolhörster, W. (1913). Messungen der Durchdringenden Strahlung im Freiballon in Grösseren

- Höhen, *Physikalische Zeitschrift*, **14**, 1153–1156.
- Kompaneets, A. (1956). The Establishment of Thermal Equilibrium between Quanta and Electrons, *Zhurnal Eksperimentalnoi i Teoreticheskoi Fiziki*, **31**, 876–885. (English translation: 1957, *Soviet Physics*, 4, 730–737).
- Koo, D. C. & Kron, R. (1982). QSO Counts – A Complete Survey of Stellar Objects to  $B = 23$ , *Astronomy and Astrophysics*, **105**, 107–119.
- Kormendy, J. & Bender, R. (1999). The Double Nucleus and Central Black Hole of M31, *Astrophysical Journal*, **522**, 772–792.
- Kormendy, J. & Richstone, D. O. (1995). Inward Bound – The Search For Supermassive Black Holes In Galactic Nuclei, *Annual Review of Astronomy and Astrophysics*, **33**, 581–624.
- Kovalev, Y. Y., Aller, H. D., Aller, M. F., et al. (2009). The Relation Between AGN Gamma-Ray Emission and Parsec-Scale Radio Jets, *Astrophysical Journal Letters*, **696**, L17–L21.
- Kovalev, Y. Y., Kellermann, K. I., Lister, M. L., et al. (2005). Sub-Milliarcsecond Imaging of Quasars and Active Galactic Nuclei. IV. Fine-Scale Structure, *Astronomical Journal*, **130**, 2473–2505.
- Kowal, G., Lazarian, A., Vishniac, E. T., & Otmianowska-Mazur, K. (2009). Numerical Tests of Fast Reconnection in Weakly Stochastic Magnetic Fields, *Astrophysical Journal*, **700**, 63–85.
- Kramer, M., Stairs, I. H., Manchester, R. N., et al. (2006). Tests of General Relativity from Timing the Double Pulsar, *Science*, **314**, 97–102.
- Krause, O., Birkmann, S. M., Usuda, T., et al. (2008a). The Cassiopeia A supernova was of Type IIb, *Science*, **320**, 1195–1197.
- Krause, O., Tanaka, M., Usuda, T., et al. (2008b). Tycho Brahe’s 1572 supernova as a standard type Ia as revealed by its light-echo spectrum, *Nature*, **456**, 617–619.
- Krolik, J. H. (1999). *Active galactic nuclei – from the central black hole to the galactic environment*. Princeton, NJ: Princeton University Press.
- Krymsky, G. F. (1977). A Regular Mechanism for the Acceleration of Charged Particles on the Front of a Shock Wave, *Doklady Akademiiy Nauk SSSR*, **234**, 1306–08.
- Krzeminski, W. (1974). The Identification and UBV Photometry of the Visible Component of the Centaurus X-3 Binary System, *Astrophysical Journal Letters*, **192**, L135–L138.
- Ku, W., Helfand, D. J., & Lucy, L. B. (1980). X-ray properties of quasars, *Nature*, **288**, 323–328.
- Kubota, A. & Makishima, K. (2005). Observational studies of stellar black hole binaries and ULXs, *ArXiv Astrophysics e-prints*. See also: Advances in Space Research, Special Issue Proceedings of 35th COSPAR Conference, Paris, France, 18–25 July 2004.
- Kulsrud, R. & Pearce, W. P. (1969). The effect of wave-particle interactions on the propagation of cosmic rays, *Astrophysical Journal*, **156**, 445–469.
- Kulsrud, R. M. (2005). *Plasma Physics for Astrophysics*. Princeton, NJ: Princeton University Press.
- Labeyrie, A. (1978). Stellar interferometry methods, *Annual Review of Astronomy and Astrophysics*, **16**, 77–102.
- Lacy, M., Miley, G., Rawlings, S., et al. (1994). 8C 1435+635: a Radio Galaxy at  $z = 4.25$ , *Monthly Notices of the Royal Astronomical Society*, **271**, 504–512.
- Lagache, G., Dole, H., & Puget, J.-L. (2003). Modelling infrared galaxy evolution using a phenomenological approach, *Monthly Notices of the Royal Astronomical Society*, **338**, 555–571.
- Lagache, G., Dole, H., Puget, J.-L., et al. (2004). Polycyclic Aromatic Hydrocarbon Contribution to the Infrared Output Energy of the Universe at  $z \sim 2$ , *Astrophysical Journal Supplement*, **154**, 112–117.
- Lagage, P. O. & Cesarsky, C. J. (1983). The maximum energy of cosmic rays accelerated by supernova shocks, *astronomy and Astrophysics*, **125**, 249–257.
- Laing, R. A. (1988). The sidedness of jets and depolarization in powerful extragalactic radio sources, *Nature*, **331**, 149–151.
- Laing, R. A. (1993). Radio observations of jets: large scales., in *Astrophysical Jets*, eds Burgarella,

- D., Livio, M., & O'Dea, C., volume 103, pp. 95–119. Cambridge: Cambridge University Press.
- Laing, R. A. & Bridle, A. H. (2002). Dynamical models for jet deceleration in the radio galaxy 3C 31, *Monthly Notices of the Royal Astronomical Society*, **336**, 1161–1180.
- Laing, R. A., Riley, J. M., & Longair, M. S. (1983). Bright radio sources at 178 MHz - Flux densities, optical identifications and the cosmological evolution of powerful radio galaxies, *Monthly Notices of the Royal Astronomical Society*, **204**, 151–187.
- Lal, D. (1972). Hard Rock Cosmic Ray Archaeology, *Space Science Reviews*, **14**, 3–102.
- Lamb, H. (1932). *Hydrodynamics (6th edition)*. Cambridge: Cambridge University Press.
- Landau, L. D. & Lifshitz, E. M. (1987). *Fluid Mechanics (2nd edition)*. Oxford: Butterworth-Heinemann.
- Larmor, J. (1884). Electromagnetic induction in conducting sheets and solid bodies, *Philosophical Magazine, Series 5*, **17**, 1–23.
- Lattes, C., Occhialini, G., & Powell, C. (1947). Observations on the Tracks of Slow Mesons in Photographic Emulsions, *Nature*, **160**, 453–456.
- Lawson, K. D., Mayer, C. J., Osborne, J. L., & Parkinson, M. L. (1987). Variations in the Spectral Index of the Galactic Radio Continuum Emission in the Northern Hemisphere, *Monthly Notices of the Royal Astronomical Society*, **225**, 307–327.
- Lazarian, A. & Vishniac, E. T. (1999). Reconnection in a Weakly Stochastic Field, *Astrophysical Journal*, **517**, 700–718.
- Le Borgne, D., Elbaz, D., Ocvirk, P., & Pichon, C. (2009). Cosmic star-formation history from a non-parametric inversion of infrared galaxy counts, *Astronomy and Astrophysics*, **504**, 727–740.
- Le Roux, E. (1961). Étude théorique du rayonnement synchrotron des radiosources, *Annales d'Astrophysique*, **24**, 71–85.
- Leavitt, H. S. (1912). Periods of 25 Variable Stars in the Small Magellanic Cloud, *Harvard College Observatory Circular*, **No. 173**, 1–2.
- Leger, A. & Puget, J. L. (1984). Identification of the 'Unidentified' IR Emission Features of Interstellar Dust?, *Astronomy and Astrophysics*, **137**, L5–L8.
- Legg, M. P. C. & Westfold, K. C. (1968). Elliptic Polarization of Synchrotron Radiation, *Astrophysical Journal*, **154**, 499–514.
- Leibundgut, B. (2000). Type Ia Supernovae, *Astronomy and Astrophysics Reviews*, **10**, 179–209.
- Leighton, R. (1959). *Introduction to Modern Physics*. San Francisco: Addison-Wesley Publications.
- Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A., & Torres-Peimbert, S. (1979). Chemical Composition and Evolution of Irregular and Blue Compact Galaxies, *Astronomy and Astrophysics*, **80**, 155–166.
- eds Lewin, W. H. G. & van der Klis, M. (2006).
- Liedahl, D. A. (1999). The X-Ray Spectral Properties of Photoionized Plasma and Transient Plasmas, in *X-Ray Spectroscopy in Astrophysics*, eds van Paradijs, J. & Bleeker, J. A. M., volume 520 of *Lecture Notes in Physics*, Berlin Springer Verlag, pp. 189–+.
- Lightman, A. P. & Eardley, D. M. (1974). Black holes in binary systems: instability of disk accretion, *Astrophysical Journal*, **187**, L1–L3.
- Lilly, S. & Cowie, L. (1987). Deep Infrared Surveys, in *Infrared Astronomy with Arrays*, eds Wynn-Williams, C. & Becklin, E., pp. 473–482. Honolulu: Institute for Astronomy, University of Hawaii Publications.
- Lilly, S. J. (1988). Discovery of a Radio Galaxy at a Redshift of 3.395, *Astrophysical Journal*, **333**, L161–L167.
- Lilly, S. J., Tresse, L., Hammer, F., Crampton, D., & LeFevre, O. (1995). The Canada-France Redshift Survey. VI. Evolution of the Galaxy Luminosity Function to  $z \sim 1$ , *Astrophysical Journal*, **455**, 108–124.
- Lin, R. P., Krucker, S., Hurford, G. J., et al. (2003). RHESSI Observations of Particle Acceleration and Energy Release in an Intense Solar Gamma-Ray Line Flare, *Astrophysical Journal Letters*,



- 595**, L69–L76.
- Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. (2006). Catalogue of high-mass X-ray binaries in the Galaxy (4th edition), *astronomy and Astrophysics*, **455**, 1165–1168.
- Longair, M. S. (1966). On the Interpretation of Radio Source Counts, *Monthly Notices of the Royal Astronomical Society*, **133**, 421–436.
- Longair, M. S. (1978). Radio Astronomy and Cosmology, in *Observational Cosmology: 8th Advanced Course, Swiss Society of Astronomy and Astrophysics, Saas-Fee 1978*, eds Maeder, A., Martinet, L., & Tammann, G., pp. 125–257. Geneva: Geneva Observatory Publications.
- Longair, M. S. (1981). *High Energy Astrophysics, first edition*. Cambridge: Cambridge University Press.
- Longair, M. S. (1988). The New Astrophysics, in *The New Physics*, ed. Davies, P., pp. 94–208. Cambridge: Cambridge University Press.
- Longair, M. S. (1995). The Physics of Background Radiation, in *The Deep Universe*, by Sandage, A.R., Kron, R.G. and Longair, M.S., eds Binggeli, B. & Buser, R., pp. 317–514.
- Longair, M. S. (1997a). Active Galactic Nuclei – The Redshift One 3CR galaxies, *Astronomy and Geophysics*, **38**, 10–15.
- Longair, M. S. (1997b). *High Energy Astrophysics, Volume 1 (revised second edition)*. Cambridge: Cambridge University Press.
- Longair, M. S. (1997c). *High Energy Astrophysics, Volume 2 (revised second edition)*. Cambridge: Cambridge University Press.
- Longair, M. S. (2003). *Theoretical Concepts in Physics: An Alternative View of Theoretical Reasoning in Physics*. Cambridge: Cambridge University Press.
- Longair, M. S. (2006). *The Cosmic Century: A History of Astrophysics and Cosmology*. Cambridge: Cambridge University Press.
- Longair, M. S. (2008). *Galaxy Formation, second edition*. Berlin and Heidelberg: Springer-Verlag.
- Longair, M. S. & Riley, J. M. (1979). Statistical evidence on the dynamical evolution of extended radio sources, *Monthly Notices of the Royal Astronomical Society*, **188**, 625–635.
- Longair, M. S., Ryle, M., & Scheuer, P. A. G. (1973). Models of extended radiosources, *Monthly Notices of the Royal Astronomical Society*, **164**, 243–270.
- Lorimer, D. & Kramer, M. (2005). *Handbook of pulsar astronomy*. Cambridge: Cambridge University Press.
- Lotz, J. M., Madau, P., Giavalisco, M., Primack, J., & Ferguson, H. C. (2006). The Rest-Frame Far-Ultraviolet Morphologies of Star-forming Galaxies at  $z \sim 1.5$  and 4, *Astrophysical Journal*, **636**, 592–609.
- Lovelace, R. V. E. & Romanova, M. M. (2003). Relativistic Poynting Jets from Accretion Disks, **596**, L159–L162.
- Lucek, S. G. & Bell, A. R. (2000). Non-linear amplification of a magnetic field driven by cosmic ray streaming, *Monthly Notices of the Royal Astronomical Society*, **314**, 65–74.
- Lund, N. (1984). Cosmic Ray Abundances, Elemental and Isotopic, in *Cosmic Radiation in Contemporary Astrophysics*, ed. Shapiro, M. M., pp. 1–26. Dordrecht: D. Reidel Publishing Company.
- Luo, D., McCray, D., & Slavin, J. (1994). The impact of SN1987A with its interstellar ring, *Astrophysical Journal*, **430**, 264–276.
- Lyne, A. G., Burgay, M., Kramer, M., et al. (2004). A Double-Pulsar System: A Rare Laboratory for Relativistic Gravity and Plasma Physics, *Science*, **303**, 1153–1157.
- Lyne, A. G. & Graham-Smith, F. (2006). *Pulsar astronomy, 3rd edition*. Cambridge: Cambridge University Press.
- Madau, P., Ferguson, H., Dickinson, M., et al. (1996). High-redshift Galaxies in the *Hubble Deep Field*: Colour Selection and Star Formation History to  $z$  4, *Monthly Notices of the Royal Astronomical Society*, **283**, 1388–1404.
- Magorrian, J., Tremaine, S., Richstone, D., et al. (1998). The Demography of Massive Dark Objects

- in Galaxy Centers, *Astronomical Journal*, **115**, 2285–2305.
- Mahoney, W. A., Varnell, L. S., Jacobson, A. S., et al. (1988). Gamma-ray observations of Co-56 in SN 1987A, *Astrophysical Journal Letters*, **334**, L81–L85.
- Majewski, S. R., Munn, J. A., Kron, R. G., et al. (1991). A proper motion and variability QSO survey to  $B = 22.5$ , in *The Space Distribution of Quasars*, ed. Crampton, D., volume 21, pp. 55–65. San Francisco: Astronomical Society of the Pacific Conference Series.
- Malkan, M. & Sargent, W. L. (1982). The Ultraviolet Excess of Seyfert I Galaxies and Quasars, *Astrophysical Journal*, **254**, 22–37.
- Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. (2005). ATNF Pulsar Catalog, *VizieR Online Data Catalog*, **7245**, 0–+.
- Manchester, R. N. & Taylor, J. H. (1977). *Pulsars*. San Francisco: W. H. Freeman and Company Ltd.
- Margon, B. & Ostriker, J. P. (1973). The Luminosity Function of Galactic X-Ray Sources - a Cutoff and a "standard Candle"?, *Astrophysical Journal*, **186**, 91–96.
- Markarian, B. E. (1967). Galaxies with an Ultraviolet Continuum., *Astrofizika*, **3**, 24–38.
- Markarian, B. E., Lipovetsky, V. A., & Stepanian, D. A. (1981). Galaxies with Ultraviolet Continuum XV, *Astrofizika*, **17**, 619–627. Translation: (1982), *Astrophysics*, **17**, 321–332.
- Marscher, A. P. (1993). Compact extragalactic radio jets., in *Astrophysical Jets*, ed. D. Burgarella, M. Livio, . C. O., volume 103 of *Astrophysics and Space Science Library*, pp. 73–94. Cambridge: Cambridge University Press.
- Marscher, A. P., Jorstad, S. G., Gómez, J., et al. (2002). Observational evidence for the accretion-disk origin for a radio jet in an active galaxy, *Nature*, **417**, 625–627.
- Marsh, T. R., Horne, K., Schlegel, E. M., Honeycutt, R. K., & Kaitchuck, R. H. (1990). Doppler imaging of the dwarf nova U Geminorum, *Astrophysical Journal*, **364**, 637–646.
- Matt, G., Fabian, A. C., & Reynolds, C. S. (1997). Geometrical and chemical dependence of K-shell X-ray features, *Monthly Notices of the Royal Astronomical Society*, **289**, 175–184.
- Matthews, T. A., Morgan, W. W., & Schmidt, M. (1964). A Discussion of Galaxies Identified with Radio Sources, *Astrophysical Journal*, **140**, 35–49.
- Matthews, T. A. & Sandage, A. R. (1963). Optical Identification of 3C 48, 3C 196 and 3C 286 with Stellar Objects, *Astrophysical Journal*, **138**, 30–56.
- Matthewson, D. S. & Ford, V. L. (1970). Polarization Observations of 1800 Stars, *Memoirs of the Royal Astronomical Society*, **74**, 139–182.
- Matz, S. M., Share, G. H., Leising, M. D., Chupp, E. L., & Vestrand, W. T. (1988). Gamma-ray line emission from SN1987A, *Nature*, **331**, 416–418.
- Mayor, M. & Queloz, D. (1995). A Jupiter-mass Companion to a Solar-type Star, *Nature*, **378**, 355–359.
- McCarthy, P. J. (2006). Galaxy Formation and Cosmology in the ELT Era, in *Scientific Requirements for Extremely Large Telescopes: IAU Symposium No. 232*, eds Whitelock, P., Dennefeld, M., & Leibundgut, B., pp. 119–129. Cambridge: Cambridge University Press.
- McCarthy, P. J., Le Borgne, D., Crampton, D., et al. (2004). Evolved Galaxies at  $z \geq 1.5$  from the Gemini Deep Deep Survey: The Formation Epoch of Massive Stellar Systems, *Astrophysical Journal Letters*, **614**, L9–L12.
- McCarthy, P. J., van Breugel, W. J. M., Spinrad, H., & Djorgovski, G. (1987). A Correlation between the Radio and Optical Morphologies of Distant 3CR Radio Galaxies, *Astrophysical Journal*, **321**, L29–L33.
- McClintock, J. E. & Remillard, R. A. (2006). *Black hole binaries*, pp. 157–213.
- McLeod, J. M. & Andrew, B. H. (1968). The Radio Source VRO 42.22.01, *Astrophysical Letters*, **1**, 243.
- McLure, R. J., Jarvis, M. J., Targett, T. A., Dunlop, J. S., & Best, P. N. (2006). On the Evolution of the Black Hole:Spheroid Mass Ratio, *Monthly Notices of the Royal Astronomical Society*, **368**, 1395–1403.



- Melia, F. & Falcke, H. (2001). The Supermassive Black Hole at the Galactic Center, *Annual Review of Astronomy and Astrophysics*, **39**, 309–352.
- Mellinger, A. (2007). Web-address: <http://home.arcor-online.de/axel.mellinger/>.
- Menjo, H., Miyahara, H., Kuwana, K., et al. (2005). Possibility of the detection of past supernova explosions by radiocarbon measurement, in *International Cosmic Ray Conference, Pune 2005*, volume 2, pp. 357–360. Mumbai: Tata Institute of Fundamental Research.
- Merritt, D. (1987). The Distribution of Dark Matter in the Coma Cluster, *Astrophysical Journal*, **313**, 121–135.
- Mestel, L. (1999). *Stellar magnetism*. Oxford: Clarendon Press.
- Mészáros, P. (2002). Theories of Gamma-Ray Bursts, *Annual Review of Astronomy and Astrophysics*, **40**, 137–169.
- Mészáros, P. & Rees, M. J. (1993). Gamma-Ray Bursts: Multiwaveband Spectral Predictions for Blast Wave Models, *Astrophysical Journal*, **418**, L59–L62.
- Metcalfe, N., Shanks, T., Campos, A., Fong, R., & Gardner, J. P. (1996). Galaxy Formation at High Redshifts, *Nature*, **383**, 236–237.
- Mewaldt, A. R. & Webber, R. W. (1990). Cosmic Ray Source Abundances Derived from High Energy Measurements of Fe-group Nuclei, in *International Cosmic Ray Conference*, volume 3 of *International Cosmic Ray Conference*, pp. 432–435.
- Meyer, P. (1979). Cosmic rays, in *Proceedings of the 16th International Conference on Cosmic Rays*, volume 2 of *International Cosmic Ray Conference*, pp. 115–XXX.
- Michell, J. (1784). On the Means of Discovering the Distance, Magnitude, etc. of the Fixed Stars, in Consequence of the Diminution of the Velocity of Their Light, in Case Such a Diminution Should be Found to Take Place in any of Them, and Such Other Data Should be Procured from Observations, as Would be Farther Necessary for That Purpose, *Philosophical Transactions of the Royal Society*, **74**, 35–57.
- Michelson, P. (1994). High Energy Gamma Ray Emission from Active Galaxies: EGRET Observations and Implications, in *The Physics of Active Galaxies*, ed. G. V. Bicknell, M. A. Dopita, & P. J. Q., volume 54 of *Astronomical Society of the Pacific Conference Series*, pp. 13–21.
- Mihos, J. C. & Hernquist, L. (1994). Triggering of Starbursts in Galaxies by Minor Mergers, *Astrophysical Journal*, **425**, L13–L16.
- Mihos, J. C. & Hernquist, L. (1996). Gasdynamics and Starbursts in Major Mergers, *Astrophysical Journal*, **464**, 641–663.
- Mikheyev, S. P. & Smirnov, A. Y. (1985). Resonance Enhancement of Oscillations in Matter and Solar Neutrino Spectroscopy, *Soviet Journal Nuclear Physics*, **42**, 913–917.
- Miller, G. E. & Scalo, J. M. (1979). The initial mass function and stellar birthrate in the solar neighborhood, *Astrophysical Journal Supplement Series*, **41**, 513–547.
- Miller, J. M., Fabian, A. C., Wijnands, R., et al. (2002). Evidence of Spin and Energy Extraction in a Galactic Black Hole Candidate: The XMM-Newton/EPIC-pn Spectrum of XTE J1650-500, *Astrophysical Journal Letters*, **570**, L69–L73.
- Miller, J. S. (1994). The Unification of Active Galaxies: Seyferts and Beyond, in *The Physics of Active Galaxies*, eds Bicknell, G. V., Dopita, M. A., & Quinn, P. J., volume 54 of *Astronomical Society of the Pacific Conference Series*, pp. 149–157.
- Minkowski, R. (1960). A New Distant Cluster of Galaxies, *Astrophysical Journal*, **132**, 908–908.
- Mioduszewski, A. J., Rupen, M. P., Walker, R. C., Schillemat, K. M., & Taylor, G. B. (2004). A Summer of SS433: Forty Days of VLBA Imaging, in *Bulletin of the American Astronomical Society*, volume 36 of *Bulletin of the American Astronomical Society*, p. 967.
- Mirabel, I. F. & Rodríguez, L. F. (1994). A Superluminal Source in the Galaxy, *Nature*, **371**, 46–48.
- Mirabel, I. F. & Rodríguez, L. F. (1998). Microquasars in our Galaxy, *Nature*, **392**, 673–676.
- Misner, C. W., Thorne, K. S., & Wheeler, J. A. (1973). *Gravitation*. San Francisco: W.H. Freeman and Co.

- Mitchell, R. J., Culhane, J. L., Davison, P. J. N., & Ives, J. C. (1976). Ariel 5 Observations of the X-ray Spectrum of the Perseus Cluster, *Monthly Notices of the Royal Astronomical Society*, **175**, 29P–34P.
- Miyoshi, M., Moran, J., Herrnstein, J., et al. (1995). Evidence for a black hole from high rotation velocities in a sub-parsec region of NGC 4258, *Nature*, **373**, 127–129.
- Moore, C. E. & Merrill, P. W. (1968). *Partial Grotrian diagrams of astrophysical interest*. Washington: US Department of Commerce, National Bureau of Standards.
- Morgan, W. W. (1958). A Preliminary Classification of the Forms of Galaxies According to Their Stellar Population, *Publications of the Astronomical Society of the Pacific*, **70**, 364–391.
- Mukai, K., Wood, J. H., Naylor, T., Schlegel, E. M., & Swank, J. H. (1997). The X-Ray Eclipse of the Dwarf Nova HT Cassiopeiae: Results from ASCA and ROSAT HRI Observations, *Astrophysical Journal*, **475**, 812–822.
- Murray, C. A. (1983). *Vectorial Astrometry*. Bristol: Adam Hilger.
- Mushotzky, R. (1980). The X-ray spectra of clusters of galaxies, in *X-ray Astronomy*, eds Giacconi, R. & Setti, G., pp. 171–179. Dordrecht: D. Reidel Publishing Company.
- Nagano, M. & Watson, A. A. (2000). Observations and implications of the ultrahigh-energy cosmic rays, *Reviews of Modern Physics*, **72**, 689–732.
- Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., et al. (1995). Discovery of a Cool Brown Dwarf, *Nature*, **378**, 463–465.
- Narayan, R. (1991). Non-axisymmetric shear instabilities in thick accretion disks, in *Structure and properties of accretion discs*, eds Meyer, X. & XXX, X., pp. 231–247.
- Narayan, R. & Goodman, J. (1991). Non-axisymmetric shear instabilities in thick accretion disks, in *Theory of accretion discs*, eds Bertout, S., Copllin-Souffrin, S., Lasota, J.-P., & Van, T. T., pp. 231–247. XXX: Éditions frontières.
- Narayan, R., Igumenshev, I. V., & Abramowicz, M. A. (2000). Self-similar accretion flows with accretion, *Astrophysical Journal*, **539**, 798–808.
- Narayan, R. & Yi, I. (1994). Advection-dominated accretion: a self-similar solution, *Astrophysical Journal Letters*, **428**, L13–L16.
- Neininger, N. (1992). The magnetic field structure of M51, *Astronomy and Astrophysics*, **263**, 30–36.
- Newman, E. T., Couch, K., Chinnapared, K., et al. (1965). Metric of a Rotating Charged Mass, *Journal of Mathematical Physics*, **6**, 918–919.
- Nicolet, B. (1980). A Plot of UBV Diagram, *Astronomy and Astrophysics Supplement*, **42**, 283–284.
- Northrop, T. G. (1963). *The Adiabatic Motion of Charged Particles*. New York: Interscience Publishing Company.
- Novikov, I. D. & Thorne, K. S. (1973). Astrophysics of black holes., in *Black holes*, eds DeWitt, C. & DeWitt, B. S., pp. 343–450. New York: Gordon and Breach Science Publishers.
- Oemler, A. J. (1974). The Systematic Properties of Clusters of Galaxies. Photometry of 15 Clusters, *Astrophysical Journal*, **194**, 1–20.
- Ohira, Y., Terasawa, T., & Takahara, F. (2009). Plasma Instabilities as a Result of Charge Exchange in the Downstream Region of Supernova Remnant Shocks, *Astrophysical Journal Letters*, **703**, L59–L62.
- Oliver, S. J., Rowan-Robinson, M., & Saunders, W. (1992). Infrared Background Constraints on the Evolution of IRAS Galaxies, *Monthly Notices of the Royal Astronomical Society*, **256**, 15P–22P.
- Oort, J. H. & Walraven, T. (1956). Polarization and Composition of the Crab Nebula, *Bulletin of the Astronomical Institutes of the Netherlands*, **12**, 285–311.
- Orosz, J. A. (2007). Home-page of Jerome A. Orosz. <http://mintaka.sdsu.edu/faculty/orosz/web/>.
- Orosz, J. A., McClintock, J. E., Narayan, R., et al. (2007). A 15.65-solar-mass black hole in an eclipsing binary in the nearby spiral galaxy M 33, *Nature*, **449**, 872–875.

- Orr, M. J. L. & Browne, I. W. A. (1982). Relativistic beaming and quasar statistics, *Monthly Notices of the Royal Astronomical Society*, **200**, 1067–1080.
- Osmer, P. S. (1982). Evidence for a Decrease in the Space Density of Quasars at  $z$  more than about 3.5, *Astrophysical Journal*, **253**, 28–37.
- Osterbrock, D. E. (1978). Optical emission-line spectra of Seyfert galaxies and radio galaxies, *Physica Scripta*, **17**, 137–143.
- Osterbrock, D. E. & Ferland, G. J. (2005). *Astrophysics of gaseous nebulae and active galactic nuclei*. Mill Valley, California: University Science Books.
- Ostriker, J. P. & Peebles, P. J. E. (1973). A Numerical Study of the Stability of Flattened Galaxies: or, Can Cold Galaxies Survive?, *Astrophysical Journal*, **186**, 467–480.
- Owen, F. N. & Ledlow, M. J. (1994). The FR I/II break and the Bivariate Luminosity Function in Abell Clusters of Galaxies, in *First Stromlo Symposium: Physics of Active Galactic Nuclei*, eds Bicknell, G. V., Dopita, M. A., & Quinn, P. J., pp. 319–323. San Francisco: Astronomical Society of the Pacific Conference Series, Volume 34.
- Owen, F. N., Ledlow, M. J., Morrison, G. E., & Hill, J. M. (1997). The Cluster of Galaxies Surrounding Cygnus A, *Astrophysical Journal Letters*, **488**, L15–L17.
- Pachoczyk, A. G. (1970). *Radio Astrophysics*. San Francisco: W.H. Freeman and Company Ltd.
- Pacini, F. (1967). Energy Emission from a Neutron Star, *Nature*, **216**, 567–568.
- Pacini, F. (1968). Rotating Neutron Stars, Pulsars and Supernova Remnants, *Nature*, **219**, 145–146.
- Page, L. (1997). Review of Observations of the Cosmic Microwave Background, in *Critical Dialogues in Cosmology*, ed. Turok, N., pp. 343–362. Singapore: World Scientific.
- Pagel, B. (1997). *Nucleosynthesis and Chemical Evolution of Galaxies*. Cambridge: Cambridge University Press.
- Panagia, N., Gilmozzi, R., Macchetto, F., Adorf, H.-M., & Kirshner, R. P. (1991). Properties of the SN 1987A Circumstellar Ring and the Distance to the Large Magellanic Cloud, *Astrophysical Journal*, **380**, L23–L26.
- Papaloizou, J. C. B. & Pringle, J. E. (1984). The Dynamical Stability of Differentially Rotating Discs with Constant Specific Angular Momentum, *Monthly Notices of the Royal Astronomical Society*, **208**, 721–750.
- Parker, E. N. (1957). Sweet's Mechanism for Merging Magnetic Fields in Conducting Fluids, *Journal of Geophysical Research*, **62**, 509–520.
- Parker, E. N. (1965). Cosmic rays and their formation of a Galactic halo., *Astrophysical Journal*, **142**, 584–590.
- Parker, E. N. (1979). *Cosmical magnetic fields*. Oxford: Clarendon Press.
- Pearson, T. J., Unwin, S. C., Cohen, M. H., et al. (1981). Superluminal Expansion of Quasar 3C273, *Nature*, **290**, 365–368.
- Pearson, T. J., Unwin, S. C., Cohen, M. H., et al. (1982). Superluminal Expansion of 3C273, in *Extragalactic Radio Sources*, eds Heeschen, D. S. & Wade, C. M., pp. 355–356. Dordrecht: D. Reidel Publishing Company.
- Pengelly, R. M. (1964). Recombination spectra, I, *Monthly Notices of the Royal Astronomical Society*, **127**, 145–163.
- Penrose, R. (1969). Gravitational Collapse: the Role of General Relativity, *Rivista Nuovo Cimento*, **1**, 252–276.
- Penzias, A. A. & Wilson, R. W. (1965). A Measurement of Excess Antenna Temperature at 4080 MHz, *Astrophysical Journal*, **142**, 419–421.
- Perley, R. A., Dreher, J. W., & Cowan, J. J. (1984). The Jet and Filaments in Cygnus A, *Astrophysical Journal*, **285**, L35–L38.
- Perlmutter, S., Gabi, S., Goldhaber, G., et al. (1997). Measurements of the Cosmological Parameters Omega and Lambda from the First Seven Supernovae at  $z > 0.35$ , *Astrophysical Journal*, **483**, 565–581.
- Peterson, B. M. (1997). *An introduction to active galactic nuclei*. Cambridge: Cambridge

- University Press.
- Peterson, B. M., Balonek, T. J., & 63 authors (1991). Steps toward Determination of the Size and Structure of the Broad-line Region in Active Galactic Nuclei. II – An Intensive Study of NGC 5548 at Optical Wavelengths, *Astrophysical Journal*, **368**, 119–137.
- Petschek, H. E. (1964). Magnetic Field Annihilation, *NASA Special Publication*, **50**, 425–+.
- Phillips, M. M. (1993). The absolute magnitudes of Type IA supernovae, *Astrophysical Journal*, **413**, L105–L108.
- Pierre Auger Collaboration (2007). Correlation of the highest-energy cosmic rays with nearby extragalactic objects, *Science*, **318**, 938–943.
- Plüschke, S., Diehl, R., Schönfelder, V., et al. (2001). The COMPTEL 1.809 MeV survey, in *Exploring the Gamma-Ray Universe*, eds Gimenez, A., Reglero, V., & Winkler, C., volume 459 of *ESA Special Publication*, pp. 55–58.
- Powell, C. F., Fowler, P., & Perkins, D. (1959). *The study of elementary particles by the photographic method*. Oxford: Pergamon Press.
- Pozdnyakov, L. A., Sobol, I. M., & Sunyaev, R. A. (1983). Comptonization and the Shaping of X-ray Source Spectra - Monte Carlo Calculations, *Soviet Scientific Reviews, Section E: Astrophysics and Space Physics Reviews*, **2**, 189–331.
- Pratt, G. W. & Arnaud, M. (2002). The mass profile of A1413 observed with XMM-Newton: Implications for the M-T relation, *Astronomy and Astrophysics*, **394**, 375–393.
- Price, P. & Fleischer, R. (1971). Identification of energetic heavy nuclei with solid dielectric track detectors: Applications to astrophysical and planetary studies, *Annual Review of Nuclear Science*, **21**, 295–334.
- Priest, E. & Forbes, T. (2000). *Magnetic reconnection*. Cambridge: Cambridge University Press.
- Priest, E. R. (1982). *Solar magneto-hydrodynamics*. Dordrecht: D. Reidel Publishing Company, Geophysics and Astrophysics Monographs, Volume 21.
- Priest, E. R. & Forbes, T. G. (1986). New models for fast steady state magnetic reconnection, *Journal of Geophysical Research*, **91**, 5579–5588.
- Pringle, J. E. & King, A. R. (2007). *Astrophysical flows*. Cambridge: Cambridge University Press.
- Puget, J.-L., Abergel, A., Bernard, J.-P., et al. (1996). Tentative detection of a cosmic far-infrared background with COBE., *Astronomy and Astrophysics*, **308**, L5–L8.
- Pye, J. P., McGale, P. A., Allan, D. J., et al. (1995). The ROSAT Wide Field Camera all-sky survey of extreme-ultraviolet sources - II. The 2RE Source Catalogue, *Monthly Notices of the Royal Astronomical Society*, **274**, 1165–1193.
- Quest, K. B. & Shapiro, V. D. (1996). Evolution of the fire-hose instability: Linear theory and wave-wave coupling, *Journal of Geophysical Research*, **101**, 24457–24470.
- Ramana Murthy, P. V. & Wolfendale, A. W. (1993). *Gamma-ray astronomy, 2nd edition*. Cambridge: University Press.
- Ramaty, R. & Lingenfelter, R. E. (1979). Gamma-ray line astronomy, *Nature*, **278**, 127–132.
- Ratcliffe, J. A. (1972). *An introduction to the ionosphere and magnetosphere*. Cambridge: Cambridge University Press.
- Reedy, R., Arnold, J., & Lal, D. (1983). Cosmic-ray record in Solar System matter, *Annual Review of Nuclear Science*, **33**, 505–537.
- Rees, M. J. (1967). Studies in Radio Source Structure – I. A Relativistically Expanding Model for Variable Quasi-Stellar Radio Sources, *Monthly Notices of the Royal Astronomical Society*, **135**, 345–360.
- Rees, M. J. (1984). Black Hole Models for Active Galactic Nuclei, *Annual review of astronomy and astrophysics*, **22**, 471–506.
- Reimer, P. J., Baillie, M. G. L., Bard, E., et al. (2004). IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP, *Radiocarbon*, **46**, 1029–1058.
- Remillard, R. A. & McClintock, J. E. (2006). X-Ray Properties of Black-Hole Binaries, *Annual Review of Astronomy and Astrophysics*, **44**, 49–92.

- Rest, A., Welch, D. L., Suntzeff, N. B., et al. (2008). Scattered-light echoes from the historical galactic supernovae Cassiopeia A and Tycho (SN 1572), *Astrophysical Journal Letters*, **681**, L81–L84.
- Reynolds, R. J. (1990). The low density ionized component of the interstellar medium and free-free absorption at high galactic latitudes, in *Low Frequency Astrophysics from Space*, eds Kassim, N. E. & Weiler, K. W., volume 362 of *Lecture Notes in Physics*, Berlin Springer Verlag, pp. 121–129.
- Richards, G. T., Strauss, M. A., Fan, X., et al. (2006). The Sloan Digital Sky Survey Quasar Survey: Quasar Luminosity Function from Data Release 3, *Astronomical Journal*, **131**, 2766–2787.
- Rindler, W. (2001). *Relativity: Special, General and Cosmological*. Oxford: Oxford University Press.
- Roberts, M. S. & Haynes, M. P. (1994). Physical Parameters along the Hubble Sequence, *Annual Review of Astronomy and Astrophysics*, **26**, 115–152.
- eds Robinson, I., Schild, A., & Schucking, E. L. (1965). Chicago: University of Chicago Press.
- Robson, I. E. (1999). *Active galactic nuclei*. Chichester: John Wiley and Sons, in association with Praxis Publishing, Chichester.
- Rochester, G. & Bulter, C. (1947). Evidence for the Existence of New Unstable Elementary Particles, *Nature*, **160**, 855–857.
- Rossi, B. & Greisen, K. (1941). Cosmic-Ray Theory, *Reviews of Modern Physics*, **13**, 240–309.
- Rowan-Robinson, M. (1968). The Determination of the Evolutionary Properties of Quasars by Means of the Luminosity-Volume Test, *Monthly Notices of the Royal Astronomical Society*, **141**, 445–458.
- Rowan-Robinson, M. (1985). *The Cosmological Distance Ladder*. New York: W. H. Freeman and Company.
- Rowan-Robinson, M. (1988). The extragalactic distance scale, *Space Science Reviews*, **48**, 1–71.
- Ruderman, M. A. & Sutherland, P. G. (1975). Theory of pulsars – polar caps, sparks, and coherent microwave radiation, *Astrophysical Journal*, **196**, 51–72.
- Rybicki, G. B. & Lightman, A. P. (1979). *Radiative Processes in Astrophysics*. New York: John Wiley and Sons.
- Sahu, K. C., Livio, M., Petro, L., et al. (1997). The Optical Counterpart to Gamma-ray Burst GRB 970228 Observed using the Hubble Space Telescope, *Nature*, **387**, 476–478.
- Sajina, A., Scott, D., Dennefeld, M., et al. (2006). The 1-1000 $\mu$ m spectral energy distributions of far-infrared galaxies, *Monthly Notices of the Royal Astronomical Society*, **369**, 939–957.
- Salpeter, E. E. (1955). The Luminosity Function and Stellar Evolution., *Astrophysical Journal*, **121**, 161–167.
- Salpeter, E. E. (1964). Accretion of Interstellar Matter by Massive Objects, *Astrophysical Journal*, **140**, 796–800.
- Sandage, A. (1957). Observational Approach to Evolution. II. a Computed Luminosity Function for K0-K2 Stars from  $M_{\{v\}} = +5$  to  $M_{\{v\}} = -4.5$ , *Astrophysical Journal*, **125**, 435–444.
- Sandage, A. R. (1965). The Existence of a Major New Constituent of the Universe: the Quasistellar Galaxies, *Astrophysical Journal*, **141**, 1560–1578.
- Sanders, D. B. & Mirabel, I. F. (1996). Luminous Infrared Galaxies, *Annual Review of Astronomy and Astrophysics*, **34**, 749–792.
- Sanders, D. B., Soifer, B. T., Elias, J. H., et al. (1988). Ultraluminous infrared galaxies and the origin of quasars, *Astrophysical Journal*, **325**, 74–91.
- Sargent, W. L. W. (1970). A Spectroscopic Survey of Compact and Peculiar Galaxies, *Astrophysical Journal*, **160**, 405–427.
- Sargent, W. L. W., Young, P. J., Lynds, C. R., et al. (1978). Dynamical Evidence for a Central Mass Concentration in the Galaxy M87, *Astrophysical Journal*, **221**, 731–744.
- Saunders, W., Rowan-Robinson, M., Lawrence, A., et al. (1990). The 60-micron and far-infrared luminosity functions of IRAS galaxies, *Monthly Notices of the Royal Astronomical Society*,



- 242**, 318–337.
- Savage, B. D. & de Boer, K. S. (1979). Observational evidence for a hot gaseous Galactic corona, *Astrophysical Journal Letters*, **230**, L77–L82.
- Scheuer, P. A. G. (1966). Radiation processes in radio astronomy, in *Plasma astrophysics: Proceedings of the International School of Physics 'Enrico Fermi'*, ed. Sturrock, P. A., volume 39, pp. 289–XXX. New York and London: Academic Press.
- Scheuer, P. A. G. (1974). Models of extragalactic radio sources with a continuous energy supply from a central object, *Monthly Notices of the Royal Astronomical Society*, **166**, 513–528.
- Scheuer, P. A. G. (1982). Morphology and power of radio sources, in *Extragalactic Radio Sources*, ed. Wade, D. S. H. & C. M., volume 97 of *IAU Symposium*, pp. 163–165.
- Scheuer, P. A. G. & Readhead, A. C. S. (1979). Superluminally expanding radio sources and the radio-quiet QSOs, *Nature*, **277**, 182–185.
- Schmidt, B. P., Kirshner, R. P., & Eastman, R. G. (1992). Expanding Photospheres of Type II Supernovae and the Extragalactic Distance Scale, *Astrophysical Journal*, **395**, 366–386.
- Schmidt, M. (1959). The Rate of Star Formation., *Astrophysical Journal*, **129**, 243–258.
- Schmidt, M. (1963). 3C 273: a Star-Like Object with Large Red-Shift, *Nature*, **197**, 1040–1040.
- Schmidt, M. (1965). Large Redshifts of Five Quasi-Stellar Sources, *Astrophysical Journal*, **141**, 1295–1300.
- Schmidt, M. (1968). Space Distribution and Luminosity Functions of Quasi-stellar Sources, *Astrophysical Journal*, **151**, 393–409.
- Schmidt, M. & Green, R. F. (1983). Quasar Evolution Derived from the Palomar Bright Quasar Survey and Other Complete Quasar Surveys, *Astrophysical Journal*, **269**, 352–374.
- Schmidt, M., Schneider, D. P., & Gunn, J. E. (1995). Spectroscopic CCD Surveys for Quasars at Large Redshift. IV. Evolution of the Luminosity Function from Quasars Detected by Their Lyman-Alpha Emission, *Astronomical Journal*, **110**, 68–77.
- Schneider, D., Schmidt, M., & Gunn, J. E. (1991). PC 1247 + 3406 - an Optically Selected Quasar with a Redshift of 4.897, *Astronomical Journal*, **102**, 837–840.
- Schneider, P. (2006). *Extragalactic Astronomy and Cosmology*. Berlin: Springer-Verlag.
- Schneider, P., Kochanek, C. S., & Wambsganss, J. (2006). *Gravitational Lensing: Strong, Weak and Micro*. Berlin: Springer-Verlag. Saas-Fee Advanced Course 33: eds. Meylan, G. and Jetzer, P. and North, P.
- Schödel, R., Ott, T., Genzel, R., et al. (2002). A star in a 15.2-year orbit around the supermassive black hole at the centre of the Milky Way, *Nature*, **419**, 694–696.
- Schönberg, M. & Chandrasekhar, S. (1942). On the Evolution of the Main-Sequence Stars, *Astrophysical Journal*, **96**, 161–171.
- Schreier, E., Levinson, R., Gursky, H., et al. (1972). Evidence for the Binary Nature of Centaurus X-3 from UHURU X-Ray Observations, *Astrophysical Journal*, **172**, L79–L89.
- Schroeder, D. (1987). *Astronomical Optics*. San Diego: Academic Press, Inc.
- Schwarzschild, K. (1916). Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie (On the Gravitational Field of a Point Mass according to Einsteinian Theory), *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften zu Berlin*, **1**, 189–196.
- Sedov, L. I. (1959). *Similarity and Dimensional Methods in Mechanics*. New York: Academic Press, 1959.
- Sekido, Y. & Elliot, H. (1985). *Early History of Cosmic Ray Studies*. Dordrecht: D. Reidel Publishing Company.
- Sellgren, K. (1984). The Near-Infrared Continuum Emission of Visual Reflection Nebulae, *Astrophysical Journal*, **277**, 623–633.
- Serkowski, K. (1973). Interstellar polarization, in *Interstellar Dust and Related Topics, IAU Symposium No. 52*, eds Greenberg, J. M. & van der Hulst, H. C., pp. 145–152. Dordrecht: D. Reidel Publishing Company.

- Serkowski, K., Mathewson, D. S., & Ford, V. L. (1975). Wavelength dependence of interstellar polarization and ratio of total to selective extinction, *Astrophysical Journal*, **196**, 261–290.
- Sérsic, J. L. (1968). *Atlas de galaxies australes*. Cordoba, Argentina: Observatorio Astronomico.
- Seward, F. D. & Charles, P. A. (1995). *Exploring the X-Ray Universe*. Cambridge: Cambridge University Press.
- Shakura, N. & Sunyaev, R. A. (1973). Black Holes in Binary Systems. Observational Appearance, *Astronomy and Astrophysics*, **24**, 337–355.
- Shapiro, M. M. (1991). A Brief Introduction to the Cosmic Radiation, in *Cosmic Rays, Supernovae and the Interstellar Medium*, eds Shapiro, M. M., Silberberg, R., & Wefel, J. P., pp. 1–28. Dordrecht: Kluwer Academic Publishers.
- Shapiro, P. R. & Field, G. B. (1976). Consequences of a New Hot Component of the Interstellar Medium, *Astrophysical Journal*, **205**, 762–765.
- Shapiro, S. L. & Teukolsky, S. A. (1983). *Black holes, white dwarfs, and neutron stars: The physics of compact objects*. New York: Wiley-Interscience.
- Shimasaku, K., Ouchi, M., Furusawa, H., et al. (2005). Number Density of Bright Lyman-Break Galaxies at  $z \sim 6$  in the Subaru Deep Field, *Publications of the Astronomical Society of Japan*, **57**, 447–458.
- Shklovsky, I. S. (1953). On the Nature of the Radiation from the Crab Nebula, *Dokladi Akademii Nauk SSSR*, **90**, 983–986.
- Shu, F. H. (1992). *Physics of Astrophysics, Vol. II*. Mill Valley, California: University Science Books.
- Shu, F. H., Adams, F. C., & Lizano, S. (1987). Star formation in molecular clouds - Observation and theory, *Annual Review of Astronomy and Astrophysics*, **25**, 23–81.
- Silberberg, R., Tsao, C. H., & Letaw, J. R. (1988). Recent improvement of spallation cross section calculations, applicable to cosmic ray physics, in *NATO ASIC Proc. 220: Genesis and Propagation of Cosmic Rays*, eds Shapiro, M. M. & Wefel, J. P., pp. 357–374.
- Silva, D. R. & Cornell, M. E. (1992). A new library of stellar optical spectra, *Astrophysical Journal Supplement Series*, **81**, 865–881.
- Simpson, J. (1983). Elemental and Isotopic Composition of Galactic Cosmic Rays, *Annual Reviews of Nuclear and Particle Science*, **33**, 323–381.
- Skilling, J. (1971). Cosmic Rays in the Galaxy: Convection or Diffusion?, *Astrophysical Journal*, **170**, 265–273.
- Skobelzyn, D. (1929). Über eine neue Art sehr schneller  $\beta$ -strahlen (On a New Type of Very Fast  $\beta$ -rays), *Zeitschrift für Physik*, **54**, 686–702.
- Smail, I., Ivison, R. J., & Blain, A. W. (1997). A Deep Sub-millimeter Survey of Lensing Clusters: A New Window on Galaxy Formation and Evolution, *Astrophysical Journal Letters*, **490**, L5–L8.
- Smart, W. (1977). *Textbook on Spherical Astronomy*. Cambridge: Cambridge University Press. Sixth edition, with revisions by R.M. Green.
- Smith, H. J. & Hoffleit, D. (1963). Light Variations in the Superluminous Radio Galaxy 3C 273, *Nature*, **198**, 650–651.
- Snellen, I. A. G., Mack, K., Schilizzi, R. T., & Tschager, W. (2004). The CORALZ sample - I. Young radio-loud active galactic nuclei at low redshift, *Monthly Notices of the Royal Astronomical Society*, **348**, 227–234.
- Soifer, B. T., Sanders, D. B., Madore, B. F., et al. (1987). The IRAS bright galaxy sample. II - The sample and luminosity function, *Astrophysical Journal*, **320**, 238–257.
- Soltan, A. (1982). Masses of quasars, *Monthly Notices of the Royal Astronomical Society*, **200**, 115–122.
- Sparke, L. & Gallagher, J. (2000). *Galaxies in the Universe: an Introduction*. Cambridge: Cambridge University Press.
- Spinrad, H., Dey, A., & Graham, J. R. (1995). Keck Observations of the Most Distant Galaxy: 8C

- 1435+63 at  $z = 4.25$ , *Astrophysical Journal*, **438**, L51–L54.
- Spitzer, L. (1962). *Physics of Fully Ionized Gases*, 2nd edition. New York: Interscience Publishers, John Wiley and Sons.
- Spitzer, L. (1968). *Diffuse matter in space*. New York: Interscience Publication.
- Spitzer, L. & Härm, R. (1953). Transport phenomena in a completely ionized gas, *Physical Review*, **89**, 977–981.
- Spitzer, L. J. & Hart, M. H. (1971). Random Gravitational Encounters and the Evolution of Spherical Systems. I. Method, *Astrophysical Journal*, **164**, 399–409.
- Springel, V., White, S. D. M., Jenkins, A., et al. (2005). Simulations of the formation, evolution and clustering of galaxies and quasars, *Nature*, **435**, 629–636.
- Stahler, S. W. & Palla, F. (2005). *The formation of stars*. New York: Interscience Publishers, John Wiley and Sons.
- Stahler, S. W., Shu, F. H., & Taam, R. E. (1980). The evolution of protostars. I - Global formulation and results, *Astrophysical Journal*, **241**, 637–654.
- Stairs, I. H. (2004). Pulsars in Binary Systems: Probing Binary Stellar Evolution and General Relativity, *Science*, **304**, 547–552.
- Starrfield, S. (1988). The classical nova outburst, in *Multiwavelength Astrophysics*, ed. Cordova, F. A., pp. 159–188.
- Stecker, F. W. (1975). Gamma ray astrophysics, in *Origin of Cosmic Rays*, eds Osborne, J. L. & Wolfendale, A. W., pp. 267–334.
- Stecker, F. W. & Salamon, M. H. (1999). Photodisintegration of Ultra-High-Energy Cosmic Rays: A New Determination, *Astrophysical Journal*, **512**, 521–526.
- Steidel, C. (1998). Galaxy Evolution: Has the "Epoch of Galaxy Formation" Been Found?, in *Eighteenth Texas Symposium on Relativistic Astrophysics and Cosmology*, eds Olinto, A., Frieman, J., & Schramm, D., pp. 124–135. River Edge, N.J. : World Scientific Publishing Company.
- Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. (1999). Lyman-Break Galaxies at  $z \geq 4$  and the Evolution of the Ultraviolet Luminosity Density at High Redshift, *Astrophysical Journal*, **519**, 1–17.
- Steigman, G. (2004). Big Bang Nucleosynthesis: Probing the First 20 Minutes, in *Measuring and Modeling the Universe*, ed. Freedman, W. L., pp. 169–195. Cambridge: Cambridge University Press.
- Stephenson, F. R. & Green, D. A. (2002). *Historical supernovae and their remnants*. Oxford: Clarendon Press.
- Stockton, A. & Ridgway, S. (1996). Optical and near IR observations of Cygnus A, in *Cygnus A – Study of a Radio Galaxy*, ed. Carilli, C. L. & Harris, D. E., pp. 1–4.
- Strong, A. W., Moskalenko, I. V., & Reimer, O. (2000). Diffuse Continuum Gamma Rays from the Galaxy, *Astrophysical Journal*, **537**, 763–784.
- Strong, A. W., Moskalenko, I. V., & Reimer, O. (2004). Diffuse Galactic Continuum Gamma Rays: A Model Compatible with EGRET Data and Cosmic-Ray Measurements, *Astrophysical Journal*, **613**, 962–976.
- Stuiver, M., Reimer, P. J., & Braziunas, T. F. (1998). Radiocarbon age calibration for terrestrial and marine samples, *Radiocarbon*, **40**, 1127–1151.
- Suganuma, M., Yoshii, Y., Kobayashi, Y., et al. (2006). Reverberation Measurements of the Inner Radius of the Dust Torus in Nearby Seyfert 1 Galaxies, *Astrophysical Journal*, **639**, 46–63.
- Sunyaev, R. A. (1980). The microwave background radiation in the direction toward clusters of galaxies, *Soviet Astronomy Letters*, **6**, 213–216.
- Sunyaev, R. A. & Titarchuk, L. G. (1980). Comptonization of X-rays in plasma clouds - Typical radiation spectra, *Astronomy and Astrophysics*, **86**, 121–138.
- Sunyaev, R. A. & Zeldovich, Y. B. (1980). Microwave Background Radiation as a Probe of the Contemporary Structure and History of the Universe, *Annual Review of Astronomy and*



- Astrophysics*, **18**, 537–560.
- Sutherland, R. S. (1998). Accurate free-free Gaunt factors for astrophysical plasmas, *Monthly Notices of the Royal Astronomical Society*, **300**, 321–330.
- Sweet, P. A. (1958). The Neutral Point Theory of Solar Flares, in *Electromagnetic Phenomena in Cosmical Physics*, ed. Lehnert, B., volume 6 of *IAU Symposium*, pp. 123–134.
- Tananbaum, H., Gursky, H., Kellogg, E. M., et al. (1972). Discovery of a Periodic Binary X-ray Source in Hercules from UHURU, *Astrophysical Journal*, **174**, L144–L149.
- Tandberg-Hanssen, E. & Emslie, A. G. (1988). *The physics of solar flares*. Cambridge and New York, Cambridge University Press.
- Tanvir, N. R., Fox, D. B., Levan, A. J., et al. (2009). A  $\gamma$ -ray burst at a redshift of  $z \sim 8.2$ , *Nature*, **461**, 1254–1257.
- Taylor, R. J. (1972). *The origin of the chemical elements*. The Wykeham Science Series, London: Wykeham Publications.
- Taylor, R. J. (1994). *The Stars: their Structure and Evolution*. Cambridge: Cambridge University Press.
- Taylor, G. (1950a). *The Formation of a Blast Wave by a Very Intense Explosion. I. Theoretical Discussion*, volume 201.
- Taylor, G. (1950b). *The Formation of a Blast Wave by a Very Intense Explosion. II. The Atomic Explosion of 1945*, volume 201.
- Taylor, J. H. & Cordes, J. M. (1993). Pulsar Distances and the Galactic Distribution of Free Electrons, *Astrophysical Journal*, **411**, 674–684.
- Thompson, C. & Duncan, R. C. (1995). The soft gamma repeaters as very strongly magnetized neutron stars - I. Radiative mechanism for outbursts, *Monthly Notices of the Royal Astronomical Society*, **275**, 255–300.
- Thompson, C. & Duncan, R. C. (1996). The soft gamma repeaters as very strongly magnetized neutron stars - II. Quiescent neutrino, X-Ray, and Alfvén wave emission, *Astrophysical Journal*, **473**, 322–342.
- Thomson, J. J. (1906). *Conduction of Electricity through Gases*. Cambridge: Cambridge University Press.
- Thorne, K., Price, R., & Macdonald, D. (1986). *Black Holes: The Membrane Paradigm*. New Haven: Yale University Press.
- Toller, G. N. (1990). Optical Observations of Galactic and Extragalactic Light - Implications for Galactic Structure, in *The Galactic and Extragalactic Background Radiation*, eds Bowyer, S. & Leinert, C., IAU Symposium No. 139, pp. 21–34. Dordrecht: Kluwer Academic Publishers.
- Toomre, A. & Toomre, J. (1972). Galactic Bridges and Tails, *Astrophysical Journal*, **178**, 623–666.
- Tremaine, S. & Gunn, J. (1979). Dynamical Role of Light Neutral Leptons in Cosmology, *Physical Review Letters*, **42**, 407–410.
- Tremonti, C. A., Heckman, T. M., Kauffmann, G., et al. (2004). The Origin of the Mass-Metallicity Relation: Insights from 53,000 Star-forming Galaxies in the Sloan Digital Sky Survey, *Astrophysical Journal*, **613**, 898–913.
- Trodden, M. (2006). Physics of the Very Early Universe: What can we learn from Particle Collider Experiments?, *Proceedings of Science*, **CMB2006**, 1–9. This electronic publication can be found at <http://pos.sissa.it/archive/conferences/027/003/CMB2006-003.pdf>.
- Tsao, C. H. & Silberberg, R. (1979). Improved Semiempirical Estimates of Cross Sections, in *International Cosmic Ray Conference*, volume 2 of *International Cosmic Ray Conference*, pp. 202–205.
- Tully, R. B. & Fisher, J. R. (1977). A New Method of Determining Distances to Galaxies, *Astronomy and Astrophysics*, **54**, 661–673.
- Turland, B. D. & Scheuer, P. A. G. (1976). Instabilities of Kelvin-Helmholtz type for relativistic streaming, *Monthly Notices of the Royal Astronomical Society*, **176**, 421–441.
- Ulrich, M. H., Boksenberg, A., Bromage, G. E., et al. (1984a). Detailed Observations of NGC 4151

- with IUE – III. Variability of the Strong Emission Lines from 1978 February to 1980 May, *Monthly Notices of the Royal Astronomical Society*, **206**, 221–238.
- Ulrich, M. H., Boksenberg, A., Bromage, G. E., et al. (1984b). Detailed Observations of NGC 4151 with IUE – III. Variability of the Strong Emission Lines from 1978 February to 1980 May, *Monthly Notices of the Royal Astronomical Society*, **209**, 479.
- van den Heuvel, E. P. J. (1987). Millisecond pulsar formation and evolution, in *The Origin and Evolution of Neutron Stars*, IAU Symposium No. 125, eds Helfand, D. J. & Huang, J.-H., pp. 393–404.
- van der Klis, M. (2000). Millisecond Oscillations in X-ray Binaries, *Annual Review of Astronomy and Astrophysics*, **38**, 717–760.
- Vashakidze, M. A. (1954). On the Degree of Polarization of the Light near Extragalactic Nebulae and the Crab Nebula, *Astronomicheskikh Tsirkular*, No. **147**, 11–13.
- Veilleux, S. (1999). Spectroscopy of Luminous Infrared Galaxies, in *Galaxy Interactions at Low and High Redshift*, eds Barnes, J. E. & Sanders, D. B., volume 186 of *IAU Symposium*, pp. 295–301.
- Velikhov, E. P. (1959). Stability of an Ideally Conducting Liquid Flowing between Cylinders Rotating in a Magnetic Field, *Zhurnal Eksperimentalnoi i Teoreticheskoi Fiziki*, **36**, 1398–1404. Translation: (1959), *Soviet Physics – JETP*, **9**, 995–998.
- Venturi, T., Cotton, W. D., Feretti, L., et al. (1996). VLBI Observations of FRI Radio Galaxies, in *Extragalactic Radio Sources*, ed. R. D. Ekers, C. Fanti, & L. Padrielli, volume 175 of *IAU Symposium*, pp. 124–126.
- Véron-Cetty, M.-P. & Véron, P. (2006). A catalogue of quasars and active nuclei: 12th edition, *Astronomy and Astrophysics*, **455**, 773–777.
- Vink, J. & Laming, J. M. (2003). On the Magnetic Fields and Particle Acceleration in Cassiopeia A, *Astrophysical Journal*, **584**, 758–769.
- Visvanathan, N. & Sandage, A. R. (1977). The Color-Absolute Magnitude Relation for E and S0 Galaxies. I - Calibration and Tests for Universality using Virgo and Eight Other Nearby Clusters, *Astrophysical Journal*, **216**, 214–226.
- Völk, H. J., Berezhko, E. G., & Ksenofontov, L. T. (2005). Magnetic field amplification in Tycho and other shell-type supernova remnants, *Astronomy and Astrophysics*, **433**, 229–240.
- Waddington, I., Dunlop, J. S., Peacock, J. A., & Windhorst, R. A. (2001). The LBDS Hercules sample of mJy radio sources at 1.4 GHz - II. Redshift distribution, radio luminosity function, and the high-redshift cut-off, *Monthly Notices of the Royal Astronomical Society*, **328**, 882–896.
- Wall, J. V. (1996). Space Distribution of Radio Source Populations, in *Extragalactic Radio Sources*, IAU Symposium No. 175, eds Ekers, R., Fanti, C., & Padrielli, L., pp. 547–552. Dordrecht: Kluwer Academic Publishers.
- Wall, J. V. & Peacock, J. A. (1985). Bright extragalactic radio sources at 2.7 GHz. III - The all-sky catalogue, *Monthly Notices of the Royal Astronomical Society*, **216**, 173–192.
- Wambsganss, J. (1998). Gravitational Lensing in Astronomy, *Living Review in Relativity*, **1**. Online article: accepted 28 August 1998; last amended 31 August 2001  
<http://www.livingreviews.org/lrr-1998-12>.
- Wandel, A. & Mushotzky, R. F. (1986). Observational determination of the masses of active galactic nuclei, *Astrophysical Journal*, **306**, L61–L66.
- Wang, W., Harris, M. J., Diehl, R., et al. (2007). SPI observations of the diffuse  $^{60}\text{Fe}$  emission in the Galaxy, *Astronomy and Astrophysics*, **469**, 1005–1012.
- Wang, W.-H., Cowie, L. L., & Barger, A. J. (2006). A Near-Infrared Analysis of the Submillimeter Background and the Cosmic Star-Formation History, *Astrophysical Journal*, **647**, 74–85.
- Warner, B. (1995). *Cataclysmic variable stars*. Cambridge, New York: Cambridge University Press.
- Warren, S. J., Hewett, P. C., Irwin, M. J., McMahon, R. G., & Bridgeland, M. T. (1987). First Observation of a Quasar with a Redshift of 4, *Nature*, **325**, 131–133.

- Wasson, J. (1985). *Meteorites: Their record of early Solar System history*. W.H. Freeman and Company.
- Watson, M. G. & King, A. R. (1991). Accretion discs in low-mass X-ray binaries., in *IAU Colloq. 129: The 6th Institute d'Astrophysique de Paris (IAP) Meeting: Structure and Emission Properties of Accretion Disks*, pp. 19–+.
- Wdowczyk, J. & Wolfendale, A. W. (1984). Galactic cosmic rays above  $10^{18}$  eV, *Journal of Physics G Nuclear Physics*, **10**, 1453–1463.
- Wdowczyk, J. & Wolfendale, A. W. (1989). Highest energy cosmic rays., *Annual Review of Nuclear and Particle Science*, **39**, 43–71.
- Webber, W. R. (1983). Cosmic ray electrons and positrons - A review of current measurements and some implications, in *NATO ASIC Proc. 107: Composition and Origin of Cosmic Rays*, ed. Shapiro, M. M., pp. 83–100.
- Webber, W. R., Kish, J. C., & Schrier, D. A. (1990a). Formula for calculating partial cross sections for nuclear reactions of nuclei with  $E \gtrsim 200$  MeV/nucleon in hydrogen targets, *Physical Review C*, **41**, 566–571.
- Webber, W. R., Kish, J. C., & Schrier, D. A. (1990b). Individual charge changing fragmentation cross sections of relativistic nuclei in hydrogen, helium, and carbon targets, *Physical Review C*, **41**, 533–546.
- Webber, W. R., Kish, J. C., & Schrier, D. A. (1990c). Individual isotopic fragmentation cross sections of relativistic nuclei in hydrogen, helium, and carbon targets, *Physical Review C*, **41**, 547–565.
- Webber, W. R., Kish, J. C., & Schrier, D. A. (1990d). Total charge and mass changing cross sections of relativistic nuclei in hydrogen, helium, and carbon targets, *Physical Review C*, **41**, 520–532.
- Weber, J. (1969). Evidence for Discovery of Gravitational Radiation, *Physical Review Letters*, **22**, 1320–1324.
- Weber, J. (1970). Anisotropy and Polarization in the Gravitational-Radiation Experiments, *Physical Review Letters*, **25**, 180–184.
- Webster, A. S. (1970). On the Diffusion-Loss Model of Cosmic Ray Electron Propagation in the Galaxy, *Astrophysical Letters*, **5**, 189–192.
- Webster, A. S. (1971). *Cosmic ray electrons and Galactic radio emission*. Cambridge: Cambridge University Ph.D dissertation.
- Webster, A. S. (1974). The spectrum of the galactic non-thermal background radiational Observations at 408, 610 and 1407 MHz, *Monthly Notices of the Royal Astronomical Society*, **166**, 355–372.
- Webster, B. L. & Murdin, P. (1972). Cygnus X-1: A Spectroscopic Binary with a Heavy Companion?, *Nature*, **235**, 37–38.
- Wefel, J. P. (1988). An overview of cosmic ray research - Composition, acceleration and propagation, in *Genesis and Propagation of Cosmic Rays*, eds Shapiro, M. M. & Wefel, J. P., pp. 1–9.
- Wefel, J. P. (1991). The Composition of the Cosmic Rays: an Update, in *NATO ASIC Proc. 337: Cosmic Rays, Supernovae and the Interstellar Medium*, eds Shapiro, M. M., Silberberg, R., & Wefel, J. P., pp. 29–56.
- Weinheimer, C. (2001). Neutrino Mass from Tritium  $\beta$ -Decay, in *Dark Matter in Astro- and Particle Physics, Proceedings of the International Conference DARK 2000*, ed. Klapdor-Kleingrothaus, H. V., pp. 513–519. Berlin: Springer-Verlag.
- Weisskopf, V. F. (1981). The Formation of Cooper Pairs and the Nature of Superconducting Currents, *Contemporary Physics*, **22**, 375–395.
- Wentzel, D. G. (1974). Cosmic-ray propagation in the galaxy - collective effects, *Annual Review of Astronomy and Astrophysics*, **12**, 71–96.
- Westfold, K. C. (1959). The polarisation of synchrotron radiation, *Astrophysical Journal*, **130**, 241–258.

- Wheeler, J. A. (1968). Our Universe: the Known and the Unknown, *American Scientist*, **56**, 1–20.
- White, D. A., Fabian, A. C., Allen, S. W., et al. (1994). A ROSAT HRI Observation of the ABELL:478 Cluster of Galaxies, *Monthly Notices of the Royal Astronomical Society*, **269**, 589–606.
- White, S. D. (1989). Observable Signatures of Young Galaxies, in *The Epoch of Galaxy Formation*, eds Frenk, C. S., Ellis, R. S., Shanks, T., Heavens, A. F., & Peacock, J. A., pp. 15–30. Dordrecht: Kluwer Academic Publishers.
- Whiteoak, J. B. (1974). The Observed Characteristics of the Local Magnetic Field, in *Galactic Radio Astronomy*, eds Kerr, F. J. & Simonson, S. C., volume 60 of *IAU Symposium*, pp. 137–150.
- Wielebinski, R. (1993). Radio Astronomy Techniques of Observing Magnetic Fields: The Galaxy, in *The Cosmic Dynamo*, eds Krause, F., Radler, K. H., & Rudiger, G., volume 157 of *IAU Symposium*, pp. 271–277.
- Wilkes, B. (1999). The Spectral Energy Distributions of Active Galactic Nuclei, in *Quasars and Cosmology*, eds Ferland, G. & Baldwin, J., volume 162 of *Astronomical Society of the Pacific Conference Series*, pp. 15–42.
- Wilkes, B. J., Tananbaum, H., Worrall, D. M., et al. (1994). The Einstein database of IPC x-ray observations of optically selected and radio-selected quasars, 1., *Astrophysical Journal Supplement*, **92**, 53–109.
- Wilkinson, P. N., Henstock, D. R., Browne, I. W., et al. (2001). Limits on the Cosmological Abundance of Supermassive Compact Objects from a Search for Multiple Imaging in Compact Radio Sources, *Physical Review Letters*, **86**, 584–587.
- Wilkinson, P. N., Polatidis, A. G., Readhead, A. C. S., Xu, W., & Pearson, T. J. (1994). Two-sided ejection in powerful radio sources: The compact symmetric objects, *Astrophysical Journal Letters*, **432**, L87–L90.
- Willingale, R., Bleeker, J. A. M., van der Heyden, K. J., & Kaastra, J. S. (2003). The mass and energy budget of Cassiopeia A, *Astronomy and Astrophysics*, **398**, 1021–1028.
- Willis, A. J., van der Hucht, K. A., Conti, P. S., & Garmany, D. (1986). An atlas of high resolution IUE ultraviolet spectra of 14 Wolf-Rayet stars, *Astronomy and Astrophysics Supplement Series*, **63**, 417–599.
- Wilson, A. S., Arnaud, K. A., Smith, D. A., Terashima, Y., & Young, A. J. (2002). Cygnus A, in *New Visions of the Universe in the XMM-Newton and Chandra Era*, ed. Jansen, F., pp. XX–XX. European Space Agency ESA SP-488.
- Wilson, A. S., Young, A. J., & Shopbell, P. L. (2000). Chandra Observations of Cygnus A: Magnetic Field Strengths in the Hot Spots of a Radio Galaxy, *Astrophysical Journal Letters*, **544**, L27–L30.
- Wolfenstein, L. (1978). Neutrino Oscillations in Matter, *Physical Review D*, **17**, 2369–2374.
- Woltjer, L. (1990). Phenomenology of Active Galactic Nuclei, in *Saas-Fee Advanced Course 20. Active Galactic Nuclei*, eds Courvoisier, T. J.-L. & Mayor, M., pp. 1–55. Berlin: Springer-Verlag.
- Woosley, S. & Janka, T. (2005). The physics of core-collapse supernovae, *Nature Physics*, **1**, 147–154.
- Woosley, S. E. (1986). Nucleosynthesis and Stellar Evolution, in *Saas-Fee Advanced Course 16: Nucleosynthesis and Chemical Evolution*, eds Audouze, J., Chiosi, C., & Woosley, S. E., pp. 1–XX.
- Woosley, S. E. & Weaver, T. A. (1986). The physics of supernova explosions, *Annual Review of Astronomy and Astrophysics*, **24**, 205–253.
- Wrobel, J. M. & Lind, K. R. (1990). The double-lobed blazar 3C 371, *Astrophysical Journal*, **348**, 135–140.
- Yanasak, N. E., Wiedenbeck, M. E., Mewaldt, R. A., et al. (2001). Measurement of the secondary radionuclides  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{54}\text{Mn}$ , and  $^{14}\text{C}$  and implications for the Galactic cosmic-ray age,

- Astrophysical Journal*, **563**, 768–792.
- Young, P. J., Westphal, J. A., Kristian, J., Wilson, C. P., & Landauer, F. P. (1978). Evidence for a Supermassive Object in the Nucleus of the Galaxy M87 from SIT and CCD Area Photometry, *Astrophysical Journal*, **221**, 721–730.
- Yukawa, H. (1935). On the Interaction of Elementary Particles. I., *Proceedings of the Physical-Mathematical Society of Japan*, **17**, 48–57.
- Zamorani, G., Henry, J. P., Maccacaro, T., et al. (1981). X-ray studies of quasars with the Einstein Observatory. II, *Astrophysical Journal*, **245**, 357–374.
- Zaritsky, D., Kennicutt, R. C., & Huchra, J. P. (1994). H II Regions and the Abundance Properties of Spiral Galaxies, *Astrophysical Journal*, **420**, 87–109.
- Zatsepin, G. T. & Kuz'min, V. A. (1966). Upper Limit of the Spectrum of Cosmic Rays, *Soviet Journal of Experimental and Theoretical Physics Letters*, **4**, 78–80.
- Zavlin, V. E. (2009). Thermal emission from isolated neutron stars: theoretical and observational aspects, in *Neutron stars and pulsars*, ed. Becker, W., volume 357 of *Astronomy and Space Science Library*. Berlin: Springer-Verlag.
- Zeldovich, Y. & Sunyaev, R. (1969). The Interaction of Matter and Radiation in a Hot-model Universe, *Astrophysics and Space Science*, **4**, 301–316.
- Zeldovich, Y. B. & Raizer, Y. P. (2002). *Physics of shock waves and high-temperature hydrodynamic phenomena*. Mineola, New York: Dover Publications. Originally published in English by Academic Press, New York in two volumes, 1966, 1967.
- Zombeck, M. V. (2006). *Handbook of Space Astronomy and Astrophysics*, 3rd edition. Cambridge: Cambridge University Press.
- Zwicky, F. & Zwicky, M. A. (1971). *Catalogue of selected compact galaxies and of post-eruptive galaxies*. Guemligen: Zwicky.

## Name Index

- Abell, George, 109, 111  
 Abraham, Robert, 805  
 Abramovitz, Milton, 227, 231  
 Abramowicz, Marek, 718  
 Adams, Fred, 384, 401  
 Aharonian, Felix, 598, 770, 771  
 Alexander, Paul, 731, 736, 738  
 Alfvén, Hannes, 639  
 Amsler, Claude, 300  
 Anderson, Carl, 31, 32, 178  
 Antonucci, Roberto, 658–660  
 Arnaud, Monique, 121  
 Arnett, David, 422  
 Arp, Halton, 642  
 Arzoumanian, Zaven, 459  
 Auger, Pierre, 31, 571  
 Axford, Ian, 611, 622, 627
- Babbedge, Thomas, 809, 810  
 Backer, Donald, 456, 457  
 Bahcall, John, 61, 63, 65, 655  
 Bahcall, Neta, 116  
 Balbus, Steven, 496  
 Ballard, K.R., 629  
 Band, David, 290, 733, 769  
 Barger, Amy, 815  
 Barthel, Peter, 660, 662, 723  
 Beck, Rainer, 568  
 Beckwith, Steven, 806, 807, 814  
 Becquerel, Henri, 159  
 Begelman, Mitchell, 736  
 Bekefi, George, 213  
 Bell(-Burnell), Jocelyn, 20, 444  
 Bell, Anthony, 611, 622, 624, 625, 628, 629  
 Bender, Ralf, 673  
 Bennett, Charles, 17  
 Berezhko, Evgeny, 631, 632
- Berezinsky, Venyamin, 583, 584  
 Best, Philip, 716  
 Bethe, Hans, 63, 179, 182, 191  
 Bignami, Giovanni, 218  
 Binney, James, 117, 167, 671, 673  
 Biretta, John, 758  
 Blaauw, Adriaan, 826  
 Blackett, Patrick, 32  
 Blain, Andrew, 812  
 Bland-Hawthorn, Jonathan, 803  
 Blandford, Roger, 276, 611, 620–622, 627,  
     712, 722, 742–744, 761, 767, 768  
 Blumenthal, George, 179, 191, 266  
 Bondi, Hermann, 483  
 Bothe, Walter, 31  
 Boyle, Brian, 647, 792  
 Bracessi, Alessandro, 643  
 Brandt, W., 794, 795  
 Bridle, Alan, 739, 740  
 Browne, Iain, 664, 665  
 Bruzual, Gustavo, 798, 799, 813, 814, 817  
 Burbidge, Geoffrey, 603, 640, 642, 648  
 Burbidge, Margaret, 648  
 Butler, Clifford, 32
- Côté, Patrick, 104  
 Calabretta, Mark, 827  
 Camenzind, Max, 441, 442  
 Cameron, Alistair, 67, 544  
 Campbell, William, 648  
 Cannon, Annie, 41  
 Cappelluti, Nico, 798  
 Carilli, Christopher, 723  
 Carter, Brandon, 474  
 Casandjian, J.-A., 764  
 Caswell, James, 248  
 Cavaliere, Alfonso, 121

- Cesarsky, Catherine, 205, 207, 568, 626, 627, 629, 631  
 Challinor, Anthony, 127, 286  
 Chambers, Kenneth, 715  
 Chandrasekhar, Subrahmanyan, 331, 469, 474, 496  
 Charlot, Stéphane, 798, 799, 817  
 Chevalier, Roger, 747  
 Chwolson, O., 129  
 Cimatti, Andrea, 806, 818  
 Clayton, Donald, 422  
 Clemmow, Phillip, 293  
 Cohen, Marshall, 747, 749, 759, 761  
 Colless, Matthew, 119  
 Compton, Arthur, 255  
 Condon, James, 728  
 Cordes, James, 459  
 Cowie, Lennox, 806, 813, 815  
 Cox, Donald, 389  
  
 Dabrowski, Youri, 690  
 Damon, Paul, 326  
 Das Gupta, Mrindal, 640  
 Davies, Rodney, 410  
 Davis, Leverett, 407  
 Davis, Raymond, 34, 61  
 de Boer, Klaas, 568  
 de Vaucouleurs, Gérard, 85, 86  
 Dermer, Charles, 552  
 Deubner, Franz-Ludwig, 57  
 Diehl, Roland, 315  
 Dirac, Adrian, 32  
 Djorgovski, George, 97  
 Dombrovski, V.A., 640  
 Dopita, Michael, 718  
 Dougherty, John, 293  
 Draine, Bruce, 383, 405–407, 409, 410  
 Dressler, Alan, 92, 97  
 Drury, Luke, 626  
 Dunlop, James, 790, 818  
 Dunn, Andrew, 119  
 Dyakov, Sergei, 275  
  
 Eardley, Douglas, 722  
 Eastman, Ronald, 430  
 Efstathiou, George, 138  
 Eichler, David, 620, 621  
 Einstein, Albert, 129, 188, 255, 271  
 Ellis, George, 473  
 Ellis, Richard, 131, 800, 805, 806  
 Ellis, Simon, 803  
 Emslie, Gordon, 353, 355  
  
 Ewen, Harold, 21  
 Ezer, D., 67  
  
 Faber, Sandra, 96, 97, 671, 678  
 Fabian, Andrew, 123, 125, 686, 687, 692  
 Falcke, Heino, 679  
 Fan, Xiaohui, 645, 793  
 Fanaroff, Bernard, 727  
 Fath, , 648  
 Felten, James, 106, 107, 787  
 Ferland, Gary, 371, 375, 650, 701–703, 705, 707, 708  
 Fermi, Enrico, 154, 616, 618, 619  
 Feynman, Richard, 272, 274, 463  
 Field, George, 392, 393, 569  
 Fisher, Richard, 96  
 Fitzpatrick, Richard, 327, 328  
 Forbes, Terry, 355, 358, 360  
 Ford, Holland, 673  
 Ford, Vincent, 407  
 Fort, Bernard, 133  
 Fowler, William, 695  
 Francis, P.J., 643  
 Frank, Juhán, 491, 496, 497, 501, 502, 504, 505, 513, 518, 520, 525, 719, 721, 722  
 Frolov, Valery, 469  
  
 Galama, T.J., 773  
 Garcia-Munoz, M., 561  
 Garrington, Simon, 663  
 Gavazzi, Raphaël, 135  
 Gehrels, Neil, 773, 774, 776, 779  
 Gel'fand, Israil, 275  
 Genzel, Reinhard, 681  
 Ghez, Andrea, 679  
 Gilli, R., 658, 794, 797  
 Ginzburg  
     Vitaly, 579  
 Ginzburg, Vitali L., 213, 239, 242  
 Ginzburg, Vitaly, 639  
 Glazebrook, Karl, 818  
 Gold, Thomas, 444  
 Goldreich, Peter, 464, 466  
 Goldsmith, Donald, 392, 393  
 Gough, Douglas, 57  
 Gould, Robert, 169, 179, 191, 266  
 Graham Smith, Francis, 444, 454, 457, 460, 461, 464, 468  
 Granot, J., 777–779  
 Green, David, 609  
 Green, Richard, 644, 647, 792  
 Greenstein, Jesse, 407



- Greisen, Eric, 827  
 Greisen, Kenneth, 300, 582  
 Grenier, I.M., 764  
 Grindlay, Jonathan, 290, 733, 769  
 Gugliucci, N.E., 738  
 Gull, Stephen, 609, 738  
 Gunn, James, 117, 118, 139, 459  
  
 Häring, N., 683, 684  
 Habing, Harm, 392, 393  
 Hall, John, 405  
 Harms, Richard, 673  
 Hasinger, Günther, 528, 794, 795  
 Hauser, Michael, 813  
 Hawking, Stephen, 473, 474, 478  
 Hawkins, Michael, 646  
 Hawley, John, 496  
 Haynes, Martha, 95, 96  
 Hazard, Cyril, 641  
 Heavens, Alan, 629  
 Heckman, Timothy, 653  
 Heitler, Wilhelm, 179, 182, 191  
 Herlofson, N., 639  
 Hess, Victor, 30, 639  
 Hewish, Antony, 20, 444  
 Hewitt, Jacqueline, 136  
 Heyvaerts, Jean, 615, 616  
 Hildebrand, Roger, 383  
 Hillas, Michael, 549, 578, 579, 635, 636  
 Hillebrandt, Wolfgang, 416, 418, 419  
 Hiltner, William, 405  
 Hinton, J., 770  
 Holloway, Nigel, 468  
 Hoyle, Fred, 483, 642, 695  
 Hubble, Edwin, 85, 86, 648, 830  
 Hulse, Russell, 454  
 Härm, Richard, 334  
  
 Illingworth, Garth, 673  
 Irwin, Michael, 645  
  
 Jackson, John, 293  
 Jackson, John D., 151, 154  
 Jackson, Robert, 96  
 Janka, Hans-Thomas, 419, 420, 422, 424, 459  
 Jansky, Karl, 19, 639  
 Jenkins, Edward, 568  
 Jennison, Roger, 640  
 Jokipii, Randy, 204, 205  
 Jones, Thomas, 630  
 Julian, William, 464, 466  
  
 Kaiser, Christian, 736  
 Kang, Hyesung, 630, 634  
 Kapahi, Vijay, 665  
 Karttunen, Hannu, 39  
 Karzas, William, 185, 252  
 Kauffmann, Guinevere, 93, 94  
 Kellermann, Kenneth, 747, 759  
 Kembhavi, Ajit, 639  
 Kennicutt, Robert, 96, 395, 820  
 Kent, Stephen, 117, 118  
 Kerr, Roy, 474  
 Khachikian, Edward, 649  
 Kiepenheuer, K.O., 639  
 King, Andrew, 491, 492, 497, 501, 502, 504, 505, 513, 518, 521, 525, 719, 722  
 King, Ivan, 116  
 Kippenhahn, Rudolf, 432, 435, 436  
 Kippenhahn, Rudolph, 39, 54, 67, 70  
 Kirshner, Robert, 430  
 Klebesadel, Ray, 771  
 Kneib, Jean-Pierre, 131  
 Koch, H. William, 179, 191  
 Kochanek, Christopher, 131  
 Kolb, Rocky, 138  
 Kolhörster, Werner, 30, 31  
 Kompaneets, Aleksander, 275  
 Koo, David, 645  
 Kormendy, John, 85, 670–673, 683  
 Kovalev, Y.Y., 763–766  
 Kramer, Michael, 444  
 Krause, Oliver, 417  
 Krolik, Julian, 639, 683, 695, 700  
 Kron, Richard, 645  
 Krymsky, Germogen, 611, 622, 627  
 Kulsrud, Russell, 207, 327, 338, 340, 355, 360, 567  
 Kuz'min, Vadim, 582  
  
 Lacy, Mark, 818  
 Lagache, Guilaine, 809, 810  
 Lagage, P.O., 626, 627, 629, 631  
 Laing, Robert, 663, 739, 740  
 Laming, Martin, 628  
 Landau, Lev, 275, 344, 346, 348, 493, 498  
 Larmor, Joseph, 464  
 Lasenby, Anthony, 127, 286  
 Lasota, Jean-Pierre, 525  
 Latter, Richard, 185, 252  
 Lawson, K.D., 594  
 Lazarian, Alexander, 409  
 Le Roux, Edouard, 228



- Lear, Egil, 611, 622, 627  
 Leavitt, Henrietta, 830  
 Ledlow, Michael, 727  
 Lee, Jae-Joon), 633  
 Leger, Alain, 382, 383  
 Legg, , 239  
 Leibundgut, Bruno, 416  
 Lequeux, James, 97  
 Liedahl, Duane, 267, 269, 270, 275, 276, 278, 686  
 Lifshitz, Evgenii, 344, 346, 348, 493, 498  
 Lightman, Alan, 213, 223, 231, 267, 275, 722  
 Lilly, Simon, 813, 818  
 Lingenfelter, Richard, 319  
 Liu, Q.Z., 529  
 Lizano, Susana, 401  
 Lochner, James, 489  
 Longair, Malcolm, 812  
 Lorimer, Duncan, 444  
 Lotz, Jennifer, 806  
 Lovelace, Roger, 761–763  
 Lucek, S.G., 628  
 Lyne, Andrew, 444, 454, 457, 460, 461, 464, 468  
 Lyttleton, Raymond, 483  
  
 Mészáros, Peter, 771, 776, 780  
 MacDonald, Douglas, 478  
 Mack, Julian, 606  
 Mackey, M.B., 641  
 Madau, Piero, 813, 815  
 Magorrian, John, 683  
 Majewski, Steven, 646  
 Malin, David, 425  
 Manchester, Richard, 448  
 Markarian, Benjamin, 648  
 Marscher, Alan, 757  
 Marsh, Thomas, 517  
 Mathewson, Donald, 407  
 Matt, G., 686, 687  
 Matthews, Thomas, 641  
 Mayor, Michel, 74  
 McCarthy, Patrick, 715, 817, 818  
 McCaughrean, Mark, 397  
 McClintock, Jeffrey, 531, 532, 534  
 McCray, Richard, 430  
 McKee, Christopher, 712  
 Melia, Fulvio, 679  
 Mellier, Yannick, 133  
 Mellinger, Axel, 7–9, 827  
 Menjo, Hiroaki, 326  
  
 Merritt, David, 118, 119  
 Mestel, Leon, 464, 467  
 Metcalfe, Nigel, 800  
 Mewaldt, Richard, 562  
 Meyer, Peter, 543  
 Michell, John, 469, 471  
 Miller, Joseph, 658–660  
 Millikan, Robert, 31  
 Minkowski, Rudolph, 641  
 Mirabel, Felix, 482, 654, 740, 741  
 Misner, Charles, 474, 475  
 Miyoshi, Makoto, 675, 678  
 Moore, XX, 648  
 Morgan, W.W., 641  
 Motz, J., 179, 191  
 Murphy, D.W., 665  
 Murray, Andrew, 825  
 Mushotzky, Richard, 489, 490, 670  
  
 Nagano, M., 634  
 Narayan, Ramesh, 722  
 Narlikar, Jayant, 639  
 Neddermeyer, Seth, 32  
 Neiningner, N., 402  
 Newman, Ted, 474  
 Niemeyer, Jens, 416, 418, 419  
 Nikolic, Bojan, 380  
 Northover, Kevin, 738  
 Northrop, Theodore, 201  
 Novikov, Igor, 469  
  
 Occhialini, Giuseppe, 32  
 Olson, Roy, 771  
 Oort, Jan, 20, 640  
 Orosz, Jerome, 482  
 Orr, M.J.L., 664  
 Osmer, Patrick, 645  
 Osterbrock, Donald, 371, 375, 650, 701–703, 705, 707, 708  
 Ostriker, Jeremiah, 102, 459, 611, 622, 627  
 Owen, Fraser, 727  
  
 Pacholczyk, Andrej, 213  
 Pacini, Franco, 444, 464  
 Pagel, Bernard, 543  
 Palla, Francesco, 393  
 Panagia, Nino, 430  
 Parker, Eugene, 354, 355, 569, 570  
 Peacock, John, 293, 790  
 Pearce, W. P., 207  
 Pearce, William, 567  
 Peebles, James, 102

- Pengelly, R.M., 372  
 Penrose, Roger, 473, 477  
 Penzias, Arno, 15  
 Peterson, Bradley, 639, 709–713  
 Petschek, Harry, 358  
 Pogson, Norman, 833  
 Pozdnyakov, L., 267, 278, 281, 282  
 Pratt, Gabriel, 121  
 Price, Richard, 478  
 Priest, Eric, 353–355, 358, 360  
 Pringle, James, 492  
 Pryce, M.H.L., 468  
 Puget, Jean-Loup, 382, 383, 813  
 Purcell, Edward, 21  
  
 Queloz, Didier, 74  
  
 Röntgen, Wilhelm, 159  
 Röttgering, Huub, 716  
 Raine, Derek, 491, 497, 501, 502, 504, 505,  
 513, 518, 521, 719, 722  
 Raizer, Yuri, 344  
 Ramaty, Reuven, 319  
 Readhead, Anthony, 665  
 Rees, Martin, 694, 743, 744, 750, 771  
 Reimer, Paula, 326  
 Remillard, Ronald, 531, 532, 534  
 Rest, Armin, 417  
 Reynolds, Christopher, 686, 687  
 Reynolds, R.J., 372  
 Richards, Gordon, 793  
 Richer, John, 392  
 Richstone, Douglas, 670–672, 683  
 Ridgway, Susan, 702  
 Riley, Julia, 727  
 Rindler, Wolfgang, 473, 752  
 Rix, Hans-Martin, 683, 684  
 Roberts, Morton, 95, 96  
 Robson, Ian, 639  
 Rochester, George, 32  
 Rodrigues, Juan, 482  
 Rodrigues, Luis, 740, 741  
 Romanova, M., 762, 763  
 Rossi, Bruno, 300  
 Rowan-Robinson, Michael, 789, 830, 831  
 Rubin, Vera, 101  
 Ruderman, Malvin, 468  
 Rybicki, George, 213, 223, 231, 267, 275  
 Ryu, Dongsu., 634  
  
 Sérsic, José Luis, 91  
 Saikia, D.J., 665  
  
 Sajina, Anna, 807  
 Salaman, M. H., 583  
 Salpeter, Edwin, 693  
 Sandage, Allan, 85, 97, 642, 648  
 Sanders, David, 654  
 Sargent, Wallace, 648, 673, 675  
 Sari, R., 777, 778  
 Savage, Blair, 568  
 Sazonov, V. N., 239  
 Scheuer, Peter, 232, 665, 742  
 Schmidt, Brian, 430  
 Schmidt, Maarten, 394, 641, 642, 644, 645,  
 647, 650, 789, 792, 793  
 Schneider, Peter, 131, 135  
 Schroeder, Daniel, 843  
 Schwarzschild, Karl, 469  
 Schwarzschild, Martin, 104  
 Sedov, Leonid, 606  
 Seyfert, Carl, 648  
 Shakura, Nicolai, 496, 501  
 Shapiro, Paul, 569  
 Shapiro, Stuart, 437, 440, 462, 473, 475  
 Shimmins, John, 641  
 Shklovsky, Iosef, 640  
 Shu, Frank, 384, 393, 401  
 Silberberg, Rein, 310, 313, 314  
 Simpson, John, 544, 545, 558  
 Skadron, George, 611, 622, 627  
 Skilling, John, 568  
 Skobeltsyn, Dmitri, 30, 32  
 Slipher, Vesto, 648  
 Smart, William, 825  
 Smith, Barham, 389  
 Sobol, I., 267  
 Soifer, Thomas, 654  
 Soltan, Andrzej, 681–683  
 Spinrad, Hyron, 818  
 Spitzer, Lyman, 327, 331, 333, 334  
 Springel, Volker, 820  
 Stahler, Steven, 393  
 Starrfield, Sumner, 521, 522  
 Stecker, Floyd, 552, 583, 584  
 Stegun, Irene, 227, 231  
 Steidel, Charles, 813  
 Steigman, Gary, 136  
 Stockton, Alan, 702, 724  
 Strong, Andrew, 191, 552, 553  
 Strong, Ian, 771  
 Suganuma, Masahiro, 713, 715  
 Sunyaev, Rashid, 165, 267, 282, 283, 496,  
 501

- Sutherland, Peter, 468  
 Sutherland, Ralph, 185, 718  
 Sweet, Peter, 355  
 Syrovatskii, Sergei, 213, 239, 242, 579, 626  
  
 Tandberg-Hanssen, Einar, 353  
 Tayler, Roger, 39, 52, 53, 543  
 Taylor, Geoffrey, 606  
 Taylor, Joseph, 454  
 Tesla, Nikola, 178  
 Teukolsky, Saul, 437, 440, 462, 473, 475  
 Thomson, John Joseph (J.J.), 170, 171, 255  
 Thorne, Kip, 474, 475, 478  
 Tremaine, Scott, 117, 139, 167, 671  
 Trodden, Mark, 139  
 Tsao, Chen-Hsiang, 310, 313, 314  
 Tully, Brent, 96  
 Turner, Michael, 138  
  
 Ulrich, Marie-Hélène, 709  
 Ulrich, Roger, 61  
  
 Völk, Heinz, 628, 631, 632  
 Véron  
     Phillippe, 580  
 Véron-Cetty  
     Marie-Paule, 580  
 van de Hulst, Henk, 20  
 van den Bergh, Sidney, 85, 805  
 van den Heuvel, Edward, 449, 515  
 van der Kris, Michiel, 528  
 VandenBerg, Donald, 44  
 Vashakidze, M.A., 640  
 Veilleux, Sylvain, 654, 655  
 Velikhov, E.P., 496  
 Vink, Jacco, 628  
 Visvanathan, N., 97  
  
 Waddington, Ian, 792  
 Wall, Jasper, 788  
 Walraven, Theodore, 640  
 Wambsganss, Joachim, 131  
 Wandel, Amri, 489, 490, 670  
 Wang, Wei-Hao, 815  
 Warren, Stephen, 645  
 Wasson, John, 162  
 Watson, Alan, 634  
 Wdowczyk, Jerzy, 550  
 Weaver, Thomas, 418  
 Webber, William, 542, 562  
 Weber, Joseph, 35  
 Weber, William, 313  
  
 Webster, Adrian, 568, 569, 594  
 Weedman, Daniel, 649  
 Wefel, John, 563  
 Weigert, Alfred, 39, 54, 67, 432, 435, 436  
 Weisskopf, Victor, 442  
 Wentzel, Donat, 205  
 Westfold, Kevin, 228, 239  
 Wheeler, John, 474, 475  
 White, Simon, 813  
 Wilkes, Belinda, 656  
 Wilkinson, Peter, 136, 737  
 Willingale, Richard, 421  
 Wilson, Andrew, 732, 735  
 Wilson, Robert, 15  
 Wolfendale, Arnold, 550  
 Woltjer, Lo, 643  
 Woon, David, 367  
 Woosley, Stan, 418–420, 422–424, 459, 521  
  
 Yanasak, N.E., 565  
 Yi, Insu, 722  
 Young, Peter, 673  
 Yukawa, Hideki, 32  
  
 Zanstra, Herman, 705  
 Zatsepin, Georgiy, 582  
 Zavlin, Vyacheslav, 460  
 Zeldovich, Yakov, 275, 282, 283, 344  
 Znajek, Ramon, 742, 761  
 Zwicky, Fritz, 111, 648

## Object Index

- 0902+34, 818  
14016+2610, 385  
1E1207.4-5209, 218, 219  
3C 9, 642  
3C 31, 725–727, 739, 747  
3C 47, 662, 663  
3C 48, 641, 642  
3C 58, 414  
3C 65, 716  
3C 66B, 725–727  
3C 75, 727  
3C 83.1B, 727  
3C 120, 747, 748  
3C 196, 641, 642  
3C 227, 641  
3C 234, 641  
3C 266, 716  
3C 270 (NGC 4261), 660, 661  
3C 273, *see Subject Index*  
3C 274 (Virgo A), 725, 726, 747  
3C 279, 669, 747, 748, 771  
3C 280, 716  
3C 286, 641, 642  
3C 295, 641  
3C 324, 716  
3C 345, 652, 669, 757  
3C 368, 716  
3C 371, 663, 664, 757  
3C 390.3, 713, 714  
3C 445, 641  
3C 454.3, 766, 767  
47 Tucanae (47 Tuc), 43, 44, 73, 76, 81, 457  
4C 21.53, 456, 457  
4U 1700-37, 452  
51 Peg, 74  
  
A 0620-00, 531  
  
A0535+262, 514, 515  
Abell 400, 727  
Abell 478, 123  
Abell 1413, 121  
Abell 2218, 110, 131  
Antennae, 88, 655, 695  
  
B1937+21, 456  
B2334+61, 461  
Becklin-Neugabauer (B–N) object, 397, 398  
Betelgeuse, 845  
BL-Lacertae objects (BL-Lac objects), 651  
  
Cartwheel galaxy, 88  
Cassiopeia A (Cas A), *see Subject Index*  
Centaurus A, 765  
Centaurus X-3 (Cen X-3), 450  
Coma cluster of galaxies (Abell 1656), *see Subject Index*  
Crab Nebula (M1, NGC 1952), *see Subject Index*  
CSO 2352+495, 737  
Cygnus A, *see Subject Index*  
Cygnus Loop, 596, 607  
Cygnus X-1 (Cyg X-1), 26, 281, 282, 452, 479, 482, 489, 531  
Cygnus X-2 (Cyg X-2), 527, 528  
Cygnus X-3 (Cyg X-3), 26  
  
 $\eta$ -Carinae, 79, 80  
    mass loss rate of, 79  
EXO 033319-2554.2, 218  
  
G1.9+0.3, 415, 609  
Galactic Centre, *see Subject Index*  
‘Geminga’, 461  
Gliese 229B, 73, 74  
GRB 030329, 773

- GRB 090423, 773  
 GRB 970228, 773  
 GRB 980425, 773  
 GRO 1744-28, 527  
 GRO J1655-40, 532  
 GRO J1744-28, 514  
 GRS 1915+105, 481, 740  
 GRS1915+105, 481  
 Guitar Nebula, 459  
 GX5-1, 527, 528  
  
 HD 209458, 75  
 HD 93131, 79  
 Hercules X-1 (Her X-1), *see Subject Index*  
 HH 30, 398, 399  
 HH 34, 398, 399  
 HH 211, 398, 399  
 Homunculus Nebula ( $\eta$ -Carinae), 80  
 HT Cas, 521  
  
 III Zw 2, 649  
 IRAS04505-2958, 655  
  
 Kepler's supernova, 414  
 Kleinmann-Low Nebula, 397, 398  
  
 Large Magellanic Cloud (LMC), 8, 9, 13, 29, 35, 415, 425, 426  
 LBDS 53W069, 818  
 LBDS 53W091, 818  
 LMC X-1, 482  
 LMC X-3, 482, 531, 534  
  
 M1, *see* Crab Nebula (M1, NGC 1952)  
 M3, 44  
 M33, 480, 481  
 M33 X-7, 480  
 M49 (NGC 4472), 104, 105  
 M51 (NGC 5194), 87, 402, 404  
 M67, 44  
 M81, 827  
 M87 (NGC 4486), *see Subject Index*  
 M106 (NGC 4258), *see Subject Index*  
 M31 (Andromeda Nebula), *see Subject Index*  
 Magellanic Clouds, 370  
 MCG -6-30-15, *see Subject Index*  
 Milky Way, 8, 9  
 Mkn 0744, 649  
 Mkn 1066, 649  
 MXB 1730-335, 527  
  
 NGC 253, 568, 569  
  
 NGC 383, 739  
 NGC 1068, 648, 658, 660, 661, 706  
 NGC 1128, 727  
 NGC 1265, 727  
 NGC 1275, 765  
 NGC 1300, 87, 88  
 NGC 2362, 44  
 NGC 2787, 87  
 NGC 3227, 713, 714  
 NGC 4051, 648, 713, 714  
 NGC 4151, 648, 650, 701, 709  
 NGC 4736, 649  
 NGC 4839, 119, 120  
 NGC 5195, 87  
 NGC 5236, 648  
 NGC 5506, 489  
 NGC 5548, 710, 711, 713–715  
 NGC 7023, 382  
 NGC 7469, 713–715  
 North Pole star, 8  
 NRAO 140, 757  
  
 OJ 287, 651, 652, 697  
 Ophiuchus molecular cloud, 385  
 Orion Molecular Clouds, 14, 396, 397  
     Cloud A, 396  
 Orion Nebula, 14, 18, 396–398  
 Orion star cluster, 73, 76, 78  
 Orion, constellation of, 396, 397  
  
 Perseus cluster of galaxies, *see Subject Index*  
 PG 0052+251, 655  
 PHL 909, 655  
 PKS 2155-304, 769  
 Plough or Great Bear, 8  
 PSR 1919+21 (CP 1919), 444, 445  
 PSR B0540-69, 447  
 PSR B0656+14, 461  
 PSR B1055-52, 461  
 PSR B1509-58, 447  
 PSR B1913+16, 454, 455  
 PSR J0538+2817, 461  
 PSR J0737-3039, 454–456  
 PSR J1119-6127, 447  
  
 QSO 0316-346, 655  
  
 RX J0852.0 – 4622, 597, 598  
 RX J1713.7 – 3946 (G347.3 – 0.5), 597  
  
 Sérsic 159-03, 123, 124  
 Sagittarius A, 826

Sagittarius A\* (Sgr A\*), *see Subject Index*  
Sanduleak –69 202, 35, 425, 426  
Scorpius X-1 (Sco X-1), 26, 527, 741  
Small Magellanic Cloud (SMC), 8, 9, 13  
SN 1006, 326, 414  
SN 1054, *see* Crab Nebula (M1, NGC 1952)  
SN 1181, 414  
SN 1572, *see* Tycho's supernova  
SN 1604, *see* Kepler's supernova  
SN 1987A, 35, 81, 307, 317, 415, 425–430  
SN1998bw, 773  
SS 433, 741, 742, 749  
SU Aur, 385  
  
Taurus molecular cloud, 385  
Trapezium stars in Orion Nebula, 397  
Tycho's supernova, 414, 417, 596  
Tycho's supernova remnant, 417, 595, 596,  
607, 609, 627, 628, 632, 633  
  
U Gem, 517, 519  
  
Vega ( $\alpha$ -Lyrae), 833, 834  
Vela supernova remnant, 28  
pulsar in, 444, 461, 463  
Vela X-1, 452  
Virgo A, *see* 3C 274 (Virgo A)  
Virgo cluster of galaxies, 26, 110, 725, 726  
VRO 42.22.01, 651  
VSSG 23, 385  
  
W50, 742  
  
X1822-371, 523  
XBT0748-676, 523  
XTE J1650-500, 536  
  
Z Cha, 517, 518

# Index

- Abell Catalogues of rich clusters of galaxies
  - selection criteria of clusters in, 111
  - space density of clusters in, 111
- Abell clusters of galaxies, 109–112
  - spatial correlations with clusters and galaxies, 111
- aberration formula, relativistic, 262
- absolute magnitude, 836
- absorption coefficient  $\chi_\nu$ , 186
  - for thermal bremsstrahlung, 186, 187
  - corrected for stimulated emission, 188
  - uncorrected for stimulated emission, 188
- absorption edges at X-ray energies, 251–255
  - K-edges, 253
- accelerated charged particles
  - polar diagram of radiation of, 171
- acceleration four-vector  $A$ , 177
- acceleration of an electron in the electrostatic field of a proton or nucleus, 179
- acceleration of high energy particles, 613–636
  - acceleration of charged particle in electric and magnetic fields, 614
  - acceleration of charged particle in time-varying magnetic fields, 614
- beyond the standard model, 627–635
- critical velocity  $v_c$  for electrostatic acceleration, 615
- diffusive shock acceleration
  - acceleration to same energy per nucleon, 633
  - in strong shock waves, 621–627
- electron runaway for electrostatic acceleration, 615, 616
- energy spectrum of cosmic rays at and above the ‘knee’, 633–635
  - for protons, helium nuclei, carbon, silicon and iron, 634
  - features of their properties to be explained, 613
- Fermi acceleration - original version, 621
- first order Fermi acceleration, 597
- general principles of acceleration, 613–614
  - dynamic, 613, 614
  - electromagnetic, 613–614
  - hydrodynamic, 613, 614
- highest energy cosmic rays, 635–636
  - Hillas diagram, 635, 636
- in solar flares, 614–616
- magnetic fields in supernova shock fronts, 628–629
- neutral sheets and, 614
  - importance of induced return currents, 616
  - importance of streaming instabilities, 616
- non-linear diffuse shock acceleration, 629–633
- reconnection of magnetic field lines and, 614
- accretion
  - as an energy source for X-ray sources, 25
  - in X-ray binary systems, 450
  - maximum energy release for Schwarzschild black hole, 450
- accretion columns in magnetic cataclysmic variables, 519–521
  - emission of far ultraviolet and soft X-ray emission from, 520
  - shock fronts in, 520
  - temperature of shocked gas in, 520
- accretion disc, thick, 477, 478
- accretion discs, *see* thin accretion discs
  - boundary layer
    - emission from, in cataclysmic variables, 518

- luminosity of, 499
  - boundary layer at inner edge of, 497
  - energy flow in, 499
  - formation of, 485
  - luminosities of, 498, 499
  - outward transfer of angular momentum, 485
  - viscous dissipation of energy in, 485
- accretion discs about supermassive black holes, 718–722
- accretion luminosity, 484
- Accretion Power in Astrophysics* (Frank, King and Raine, 491, 719
- accretion power in astrophysics, 483–537
  - accreting binary systems, 516–531
  - accretion in binary systems, 506–515
  - black holes in X-ray binaries, 531–537
  - Eddington limiting luminosity, 486–488
  - efficiency of the accretion process, 483–486
    - for neutron stars, 484
    - for white dwarfs, 484
    - onto black holes, 484
  - general considerations, 483–491
  - thick discs and advective flows, 504–505
  - thin accretion discs, 491–504
- accretion radius, *see* capture, or accretion, radius
- action integral in Lagrangian mechanics, 200, 201
- Active Galactic Nuclei* (Krolik), 639
- Active Galactic Nuclei* (Robson), 639
- active galactic nuclei, 648
  - ‘blue-bump’ component in spectra of, 491
  - broad-line emission from, 701
    - absence of forbidden lines in, 701
    - broadening of, 701
    - collisional de-excitation and, 701
    - filling factors for, 701
    - number densities in, 701
    - Thomson scattering in, 701
  - continuum radiation
    - polarisation of, 700
  - emission line regions in, 701–715
  - high excitation lines in spectra of, 700
  - model for, 698
  - narrow- and broad-line emission in spectra of, 702
  - narrow-line emission from, 702
    - particle densities in, 702
    - permitted and forbidden lines from, 702
  - photoexcitation and photoionisation of gas clouds in, 699
  - ratio of black hole to spheroid masses, 819, 821
  - reprocessing of the X-ray emission, 700
  - Type 1, 657, 794
  - unobscured, 657, 794
- active galactic nucleus
  - model for, 701
- active galaxies, 639–665
  - blazars
    - superluminal sources and  $\gamma$ -ray sources, 651–653
  - Low Ionisation Nuclear Emission Regions (LINERS), 653
  - lower limit to size from time variability, 669
  - mass-to-luminosity ratio  $M/L$  in central regions, 670
  - quasars, 641–647
  - radio galaxies
    - high energy astrophysics and, 639–640
  - Seyfert galaxies, 648–651
  - Ultra-Luminous Infrared Galaxies (ULIRGs), 654–656
  - unification schemes for active galaxies, 658–665
  - X-ray surveys of active galaxies, 656–658
- adaptive optics, 7, 844
- adiabatic changes in classical mechanics, 200
- adiabatic expansion
  - of a magnetic field, 337
- adiabatic inflow-outflow solutions (ADIOS), 722
- adiabatic invariance, 203
  - principle of, 199
- adiabatic invariants, 570
  - conservation of, in a time-varying magnetic field, 614
- adiabatic loss problem and the acceleration of high energy particles, 607–611
- adiabatic losses, 587–588
  - condition for importance of, 588
  - instantaneous dynamics of the expansion and, 588
  - non-relativistic
    - in an expanding flow, 587
    - in terms of momentum, 588
  - velocity distribution inside expanding sphere, 588
- adiabatic motion of charged particle, 146



- Adiabatic Motion of Charged Particles* (Northrop), 201
- Advanced Camera for Surveys (ACS), 135, 801
- advection, 718–720
- advection dominated accretion flows (ADAFs), 718, 719, 721, 722
- equations of conservation of mass, angular momentum and energy, 720
- plot of the accretion rate against the surface density, 720, 721
- radiative efficiency  $\eta$  of, 718
- super-Eddington accretion in, 722
- thermal stability of, 721, 722
- viscous stability of, 721, 722
- advective transport of mass and energy, 504–505
- supermassive black holes and, 505
- through black hole horizon, 505
- Airy diffraction pattern, 841, 843, 844
- Airy disc, 841, 844
- Aitoff projection, 828
- Akeno Giant Air Shower Array (AGASA), 571, 575
- Alfvén and hydromagnetic waves in interstellar medium, 205–207
- damping rate by neutral particles, 207
- energy density of, 206
- growth rate of, 206
- momentum density of, 206
- Alfvén radius, 511–513
- for white dwarfs, 512
- Alfvén speed, 206, 207, 352, 354, 357, 358, 567, 568, 622
- alignment effect in radio galaxies, 651, 716, 717
- shock excitation of emission line regions, 715–718
- alignment of interstellar grains, 405–407
- magnetic field parallel to optical polarisation, 407
- physical mechanisms for, 406
- Barnett effect, 406
- paramagnetic dissipation, 407
- Rowland effect, 406
- suprathermal processes, 406
- $\alpha$ -discs, 496, 501, 502, 720
- AM Herculis binaries, 218
- ambipolar diffusion, 341
- Ampère’s theorem, 355
- Anglo-Australian Telescope, 644, 647
- Anglo-Australian Telescope 2dF survey (AAT 2dF), 4, 85, 89, 111, 112
- angular cyclotron frequency, 196
- angular diameter distance, 130
- in general relativity, 470–472
- angular frequency  $\omega_0$  of electron in atom, 147
- angular gyrofrequency, 196, 201, 207
- non-relativistic, 221
- relativistic, 222, 233
- angular momentum transport by viscosity, 497, 498
- angular plasma frequency, 486
- angular resolving power, 838
- anomalous resistivity of a plasma, 359
- anomalous X-ray pulsars, 458
- location on  $P - \dot{P}$  diagram, 458
- antenna temperature, 854
- minimum detectable, 854
- aperture grading, 844
- aperture synthesis, 845–848
- Earth-rotation, 848
- principles of, 23
- apodisation, 844
- Apollo 12 and the Surveyor satellite, 161
- Apollo 14, 162
- Apollo 17, 161
- apparent magnitude
- bolometric, 834
- definition of, 833
- Archimedean spiral, 343
- Ariel-V satellite, 794
- ASCA Large Sky Survey, 794
- ASCA X-ray observatory, 597, 660, 795
- associated Legendre functions, 58
- asteroids
- asteroid belt and, 162
- parent bodies of meteorites, 162
- astronomical seeing, 844, 845
- astronomical unit (AU), 829
- astronomical units, 829
- astroparticle physics, 140
- Astrophysical Flows* (Pringle and King), 492
- Astrophysics of Gaseous Nebulae and Active Galactic Nuclei, The* (Osterbrock and Ferland), 371, 701, 702
- asymptotic giant branch stars, 316
- Atacama Large Millimetre Array (ALMA), 15
- atmosphere as convertor for cosmic rays, 549
- atmospheric turbulence and astronomical seeing, 844, 845

- ATOM telescope, 769
- atomic binding energy, 147
- Auger air-shower array, 34
- Auger electrons, 687
- Auger ultra-high energy cosmic ray observatory, 300
- aurorae, 351
  - green and red lines of oxygen in, 351
- auroral zone, 351
- Australia Telescope Compact Array, 429, 430
- Australia Telescope National Facility (ATNF), 23
- Avogadro's number, 192, 298
- Baade-Wesselink method, 430, 830
- background intensities in ground-based observations, 835, 850
- background radiation
  - submillimetre and far-infrared
    - contribution of active galactic nuclei, 815
    - main contributors to, 816
  - ultraviolet
    - decrease at large redshifts, 814, 815
    - decrease in intensity from  $z = 1$  to present epoch, 815
- Baksan Neutrino Observatory in the northern Caucasus mountains, 63
- Balmer absorption line index  $H\delta_A$  as age indicator, 94
- Balmer break, or discontinuity,  $D_n(4000)$  as age indicator, 94
- Balmer continuum absorption, 837
- Balmer decrement, 372, 703, 708
- Balmer series of hydrogen, 491, 642, 649, 699, 703, 708
- BeppoSAX gamma-ray telescope, 317, 318
- Bernoulli's equation, 346
- beryllium-10  $^{10}\text{Be}$  cosmic ray clock, 564
  - production ratio of, 564
- Bessel functions  $J_0(z)$ ,  $J_1(z)$ , 841
- betatron, 213
- Bethe-Bloch formula, 153–154, 178, 183
- bias parameter, 133
- BIMA Millimetre Array, 127, 128
- binary pulsars, 454–456
- binary star systems, 506–509
  - close, 506
  - contact binaries, 506
    - common envelope of, 506
    - mass-to-luminosity relation, 507
  - equipotential surfaces in the rotating system, 506, 507
  - evolution of stars in, 507, 508
  - feeding the accretion disc, 509–511
    - Roche lobe overflow, 509, 510
    - stellar mass loss and winds, 509, 510
  - mass transfer in, 507, 508
  - non-contact close binaries, 507
  - periods of, 506
  - role of magnetic fields, 511–515
    - accretion columns and, 512
    - magnetic pressure of, 511
    - mass flow onto magnetic poles, 511, 512
    - ram pressure and, 511
  - spectroscopic binaries, 506
  - statistics of, 506
  - symbiotic stars and, 509, 516
  - visual binaries, 506
- bipolar outflows, 386, 398
  - magnetic fields in, 398
  - model for, 398, 400
  - molecular beams in, 398
  - origin of, 401
    - magnetic fields and, 402
  - polarisation observations of, 398
  - similarity to extragalactic radio sources, 398, 402
- BL-Lacertae objects (BL-Lac objects), 20, 651, 652, 663, 664, 745
  - associated with FR I radio sources, 653
  - double-sided radio jets in, 664
  - highly variable radio sources, 651
  - low-redshift sources, 651
  - observation of, underlying FR I radio sources, 663
  - polarisation of, 700
  - rapid deceleration of radio jets in, 664
  - superluminal motions in, 653
- Black hole physics : basic concepts and new developments* (Frolov and Novikov), 469
- black holes, 84, 136, 413, 469–482
  - accretion luminosity of, 500
  - angular momentum on last stable orbit, 500
  - characteristic growth rate by accretion, 693
  - circular velocities about, 688–692
  - condition for matter to fall into, 499
  - dragging of inertial frames, 475
  - electrodynamics of, 478
  - elementary considerations, 669–670
  - ergospheres of rotating, 477
  - evaporation of, 478
  - extraction of rotational energy from rotating, 477

- ‘flickering’ of the X-ray intensity and, 488, 489
- formation and evolution of galaxies and, 685
- general case in general relativity, 474–479
- Hawking radiation from very low mass, 478
- horizon of rotating black hole, 475
- in X-ray binaries, 25, 531–537
  - different active states of, 531, 532
  - disc fraction  $f$ , 531
  - hard state, 531, 534
  - hard state and presence of radio jets, 534
  - high frequency quasi-periodic oscillations (QPOs), 535
  - hot corona in, 535, 537
  - increase in frequency of QPOs with luminosity, 535
  - iron fluorescence lines, 532, 536–537
  - luminosity of accretion disc, 533, 534
  - power density spectrum of the variability, 531
  - quasi-periodic oscillations (QPOs), 531, 532, 534–536
  - steep power-law, 531
  - steep power-law state, 534–535
  - temperature distribution in accretion disc about, 533
  - thermal state, 531, 533
- last stable orbit, 485, 488, 491, 499, 500, 505, 536, 537, 668, 688–692, 718
  - binding energies of particles on, 668
  - evidence for, 533
- light-travel time across the last stable orbit, 488
- magnetic fields threading, 477, 478
- mass estimates for, in X-ray binaries, 479, 480
- mass from kinematics of nuclear gas clouds, 490
- masses from time variability, 490
- maximally rotating, 476
- maximum angular momenta of, 475
- maximum energy release of Schwarzschild, 476, 485
- most compact objects of mass  $M$ , 668
- most powerful energy sources in astrophysics, 668
- observational evidence for, 479–482
- predicted line shapes of the fluorescent 6.4 keV line, 690, 691
  - double-horned appearance, 691–692
- primordial, 478
- properties of, 667–668
- resistivity of, 478
- Schwarzschild, 476, 667
  - efficiency of energy conversion, 681
  - gravitational and Doppler shifts on last stable circular orbit, 688
  - gravitational redshift from, 667
  - last stable circular orbit, 667, 668, 691
  - maximum binding energy on last stable orbit, 668
  - maximum redshift on last stable circular orbit, 692
  - predicted line shapes of fluorescent 6.4 keV line, 690
  - red and blue shifts on last stable circular orbit, 690
  - surface of infinite redshift, 667
  - trajectories of light rays from, 690
  - velocity on last stable circular orbit, 667, 688, 690
- sketches of, in X-ray binaries, 482
- specific angular momentum of, 499
- static radius about rotating, 475
- supermassive, 136, 782
  - epoch of maximum quasar activity, 792
  - non-thermal radiation processes and, 782
- temperature of, 478
- temperature of gas at last stable orbit, 491
- Black Holes – the Membrane Paradigm*, 478
- black holes in our Galaxy
  - X-ray spectra of, 692
- black holes in the nuclei of galaxies, 667–696
  - circular velocities about, 688–692
  - dynamical estimates of masses of, 670–672
  - dynamical evidence for, 670–681
  - elementary considerations, 669–670
  - examples of dynamical estimates of masses of, 672–681
- growth of, 693–696
  - accretion and, 693
  - advective transport of matter and, 694
  - compact star clusters and, 695
  - dissipation processes and, 695
  - feedback mechanisms and, 695
  - Rees diagram, 694–696
  - Salpeter time-scale, 693–694
  - star formation and evolution and, 695
  - transfer of angular momentum and, 695
  - ULIRGs and, 695
- properties of, 667–668

- Soltan argument for, 681–683
  - average mass density in the Universe in massive black holes, 682
  - average mass of massive black holes in  $L^*$  galaxies, 683
- spheroid masses and, 683–685
- X-ray observations of fluorescence lines and, 685–692
- black holes in X-ray binaries and active galactic nuclei, 488–491
- black-body radiation
  - intensity of, 240, 853
  - Rayleigh-Jeans limit of, 240, 241
  - spectrum of, 5
- blazars, 652, 653, 659, 663, 757, 763, 765–767, 769, 770
  - association with intense  $\gamma$ -ray sources, 653
  - high degrees of linear polarisation, 653
  - relativistic beaming and, 757
  - superluminal motions in, 653
  - superluminal sources and  $\gamma$ -ray sources, 651–653
  - variability of, 669
- blue sequence or blue cloud, 89
  - avoid regions of rich clustering, 93
  - properties of galaxies of, 89
- Bohr model of the atom, 147
- Bohr radius of the hydrogen atom, 190
- bolometric absolute magnitude, 836
  - of Sun, 836
- bolometric flux density, 836
- Boltzmann distribution, 187, 328, 364
- Boltzmann equation, 275, 286
  - collisionless, 671
  - evolution of photon occupation number and, 275
- Boltzmann relation, 272
- Bose–Einstein distribution
  - as a solution of Kompaneets equation, 278
- Bose–Einstein spectrum, 282
- Bose–Einstein statistics, 442
- bound-free absorption, *see* photoelectric absorption
- bound-free absorption in stars, 52
- bow shock, 350
  - density enhancement across, 351
- Boyer–Lindquist coordinates, 474
- braking index, 445, 447
  - energy loss from pulsars and, 445
  - for magnetic dipole radiation, 447
  - magnetic braking and, 445
- ‘braking radiation’, *see* bremsstrahlung
- bremsstrahlung, 109, 119, 127, 145, 169, 178–194, 330, 831
  - collision parameters  $b_{\max}$  and  $b_{\min}$  for, 179, 182, 587
  - cooling rate, 123
  - emissivity of, 129
  - hot intracluster gas, 735
  - low frequency spectrum of, 181, 182
  - non-relativistic energy loss rate, 182–183
  - non-thermal, 318
  - relativistic, 189–194
    - average energy of photons emitted in, 194
    - catastrophic losses in the atmosphere, 193
    - collision parameters  $b_{\max}$  and  $b_{\min}$  for, 189–191
    - correction for electron-electron interactions, 191
    - critical energy, 193
    - in terms of the photon number flux density, 193
    - radiation length  $X_0$  for, 191
    - radiation lengths for hydrogen, air and lead, 193
    - the low energy  $\gamma$ -ray emission of the interstellar medium and, 194
    - total energy loss rate, 191–193
    - total stopping power in different materials, 191, 193
  - spectral emissivity of, 121
  - spectrum of, 121, 129
  - thermal, 183–189, 724, 725
    - absorption, 186–189
    - Gaunt factors for, 184
    - Gaunt factors for radio wavelengths, 184
    - Gaunt factors for X-ray energies, 184
    - mass of gas and dark matter in clusters of galaxies and, 186
    - spectral emissivity of, 183–186
    - total energy loss rate of, 184
  - X-ray, 431
- bremsstrahlung absorption in stars, 52
- brightness temperature, 240, 241, 651, 745, 853
  - Rayleigh-Jeans approximation for, 853
- broad-line regions, 707–709
  - absence of forbidden lines, 707
  - evidence for photoexcitation and ionisation, 709
  - ionisation parameter in, 708
  - little dust extinction in, 709

- opacity of Lyman- $\alpha$  lines, 708
- photoexcitation and ionisation in, 708
- physical properties of, 708
- presence of singly-ionised iron, 708
- reverberation mapping of, 708
- semi-forbidden lines, 707
- variability of, 708
- brown dwarfs, 73, 74, 136
  - discovered in 2MASS survey, 74
  - discovered in Pleiades, Orion and  $\rho$  Ophiuchus clusters, 74
  - discovered in Sloan Digital Sky Survey (SDSS), 74
- Buckingham  $\Pi$  theorem, 606
- BUGS experiment of Ariel-VI mission, 546, 547
- buoyancy
  - hot gas bubble in the Galactic plane and, 569
- Byurakan Observatory, 648
- Calar Alto telescope, 596
- CalTech Submillimetre Observatory (CSO), 15, 127, 286
- Canada-France Redshift Survey, 813
- canonical coordinates, 200
- canonical momentum, 200
  - of particle in a magnetic field, 200
- capture, or accretion, radius, 529, 530
- carbon burning, 71
- carbon monoxide (CO) map of Galaxy, 18
- carbon recombination lines in gaseous nebulae
  - very high order transitions, 373
- carbon-nitrogen-oxygen (CNO) cycle, 49, 50, 53, 55, 69, 80, 81, 521, 522
- Cassegrain telescope, 843, 845
- Cassiopeia A (Cas A), 317, 318, 365, 415, 421, 422, 595, 602–604, 607, 608, 610, 627, 628, 640
  - as a type IIb supernova, 421
  - decrease in flux density of, 746
  - equipartition magnetic flux density, 603
  - kinetic energy of optical filaments, 603
  - minimum energy requirements for synchrotron radiation, 603
  - Type IIb supernova, 596
- cataclysmic variables, 419, 483, 488, 509, 511, 516–522
  - accretion columns in magnetic, 519–521
  - AM Herculis stars, 516, 517
  - classical novae, 516, 521, 522
    - event rate in our Galaxy and M31, 521
    - thermonuclear runaway and, 516, 522
  - dwarf novae, 516, 518, 519, 521
    - eclipse mapping of, 517, 518
    - temperature mapping, 517, 518
  - intermediate polars, 516
  - magnetic, 516
  - novae-like stars, 516
  - polars, 516, 517
  - recurrent novae, 516
  - strong emitters in the 1 – 10 keV X-ray wavebands, 519
  - strong emitters in the EUV and soft X-ray wavebands, 519
  - strong winds from, 521
  - symbiotic stars, 516
- Catalogue of selected compact galaxies and of post-eruptive galaxies* (Zwicky), 648
- causality relation, 669
- cD galaxies, 641, 651
- celestial equator, 825, 827
- celestial hemisphere
  - north, 827
  - south, 827
- celestial sphere, 828
- central limit theorem, 577, 787, 849
  - Gaussian statistics and, 849
- Cepheid variables, 830
  - luminosity–period relation for, 830
- Cerro Tololo InterAmerican Observatory, 13
- ChaMP study, 794
- Chandra Deep Fields, 794
- Chandra X-ray Observatory, 27, 124, 125, 414, 421, 429, 595, 596, 723–725, 732, 781, 794
- Chandrasekhar limit, or mass, 417–419, 435–443, 508
  - for neutron stars, 437
  - for white dwarfs, 437
- charge exchange current-driven instabilities, 629
- charge-coupled devices (CCD), 7, 850
- charged particles in magnetic fields
  - dynamics in time-varying field, 197–201
    - adiabatic invariant approach to, 200–201
    - physical approach to, 197–200
  - dynamics of, 195–207
    - in static uniform field, 195–197, 213–214

- scattering by Alfvén and hydromagnetic waves, 205–207
- scattering by irregularities in the field, 202–205
- spiral motion in uniform field, 196
- chemical potential  $\mu$ , 270, 271, 282
- Cherenkov radiation, 291–297
  - Cherenkov cone, 296
  - condition for, 293
  - energy loss rate per unit bandwidth, 297
  - ‘shock wave’ interpretation of, 292
- circumstellar disc, 386
- Classical Electrodynamics* (Jackson), 141
- classical electron radius, 257
- classical novae, *see* cataclysmic variables, classical novae
- clusters of galaxies, 109–140
  - Bautz-Morgan classification, 112, 113
  - central concentration of galaxies and central profile, 112, 113
  - central mass density of, 116
  - core radius, 113, 115
  - crossing time, 118
  - dark matter in, 135–140
  - galaxy content, 112, 113
  - isothermal gas spheres and, 113–117
  - mass segregation, 112, 113
  - morphologies of, 109–112
  - most massive galaxies in, 167
  - regular, intermediate and irregular, 111–113
  - symmetry, 112, 113
  - X-ray emission of, 27
- clusters of stars, 42
- coincidence counting, 31
- collision frequency for electrostatic collisions between particles  $v_c$ , 614
- collision of high energy particle with stationary electron
  - duration of, 146
  - limits to collision parameters, 145–148
    - relativistic case, 152–153
  - non-relativistic treatment, 144–145
    - maximum energy loss, 144
  - relativistic treatment, 152–153
- collision parameters, 144
  - maximum and minimum for electrostatic scattering, 331
- collision time of particles in a plasma, 330
- collisionless plasma, 335
- colour index
  - definition of, 836
- colour-colour diagram for stars, 837
- colour-magnitude diagram for stars, *see* Hertzsprung-Russell diagram
- colours
  - definition of, 836
- Coma cluster of galaxies (Abell 1656), 26, 117–120
  - core radius of, 116
  - mass of, 118, 832
  - mass-to-luminosity ratio, 119
  - X-ray image of, 119
- comoving coordinates, 682
- comoving radial distance coordinate, 682, 786
- comoving volume
  - variation with redshift, 784
- compact extragalactic sources and superluminal motions, 745–780
  - compact radio sources, 745–747
  - $\gamma$ -ray bursts, 771–780
  - $\gamma$ -ray sources in active galactic nuclei, 764–771
  - relativistic beaming, 750–758
  - superluminal motions, 747–750
  - superluminal source population, 759–763
  - synchro-Compton radiation and the inverse Compton catastrophe, 763–764
- compact HII region
  - spectrum at radio wavelengths of, 188, 189
- compact radio sources, 745–747
  - evidence for relativistic particles in, 745
  - relativistic bulk motion in, 291
  - variability of, 289
- Compton effect, 260
- Compton Gamma-Ray Observatory (CGRO), 316–318, 320, 653, 669, 764, 765
  - Burst and Transient Source Experiment (BATSE), 514, 771, 772
  - EGRET instrument of, 28, 29, 551, 552, 764
- Compton optical depth, 269, 270, 276, 280, 283, 284
- Compton scattering, 125, 259–261
  - average energy change of photon in, 269
  - average energy gain of photons by, 268
  - derivation of formulae for, 259–261
  - exchange of energy between electrons and radiation field, 260
  - inverse, 782
  - Klein–Nishina cross-section, 260–261
  - probability distribution for a single scattering, 285

- recoil effect, 260
- Compton scattering optical depth, 126
- Comptonisation, 267–282, 535, 620
  - basic physics of, 267–271
  - Bose-Einstein distribution
    - formation of, 270, 271
    - with finite chemical potential  $\mu$ , 271
  - Compton optical depth, 269, 270
  - condition for significant distortions of photon spectrum, 269
  - examples of astrophysical applications, 268
  - interchange of energy between matter and radiation and, 268–270
    - differential equation for, 269
  - Kompaneets equation, 275–282
  - number of scatterings to approach saturation, 270
  - occupation number, 272–275
  - recoil effect in, 268
- computer simulations
  - hydrodynamical simulations of galaxy collisions, 820
  - origin and evolution of cosmic structures and, 820
- concentration index  $C = (R_{90}/R_{50})$ , 94
- conductivity of a plasma, 145, 464
- cone diagram of the distribution of galaxies, 111
- conservation of angular momentum, 471, 484
- conservation of energy for Newtonian gravity, 471, 472, 484
- conservation of energy in general relativity, 472, 484
- conservation of mass, 53
- convection dominated accretion flows (CDAFs), 722
- convective transport of energy in stars, 50, 54
  - condition for, 50, 66
  - in main sequence stars, 67
  - in pre-main sequence stars, 67
  - in red giant stars, 67
  - of different masses on the main sequence, 68
- convective transport of mass and energy, 505
- cooling flows in clusters of galaxies, 123–125
- cooling function
  - generalised, 719
- Cooper pairs, 442
- coordinate systems and projections used in astronomy, 8
- coordinate systems in astronomy, 825–829
  - coordinate time in general relativity, 470, 688
  - coordinate-space diagram for diffusion-loss equation, 209
- Copernicus satellite, 368, 369
- coronal loops, 338, 339, 342, 353
- coronal mass ejection events, 344
- coronene, 383
- correlation between far-infrared luminosity and radio luminosity of galaxies, 728, 730
  - interpretation in terms of starbursts, 729
- COS-B satellite, 28
- Cosmic Background Explorer (COBE), 16, 17, 410
  - DIRBE instrument of, 12–14
  - FIRAS instrument of, 283
- The Cosmic Century: A History of Astrophysics and Cosmology* (Longair), ii–iv, 3, 5, 53, 213, 639
- Cosmic Microwave Background Radiation, 15–18, 109, 125, 126, 410, 589, 731, 733, 755, 831
  - cosmological fluctuations in, 17
  - dipole component of, 15–17
  - dipole temperature distribution from moving reference frame, 755
  - distortions from a perfect black-body spectrum, 282
    - due to energy injection after the recombination era, 283
    - due to energy injection prior to the recombination era, 282
    - limits to, 284
  - fluctuations in, 820
  - motion of the Solar System relative to, 16, 17
  - radiation temperature of, 15
  - Sunyaev-Zeldovich distortions of, 125–127, 286
- cosmic ray astrophysics, 29–34
  - extensive air showers, 31
  - from space and from the ground, 32–34
  - history of, 29–32
  - ionisation of the atmosphere with increasing altitude, 30, 31
- cosmic ray clocks, 548
- cosmic ray electrons
  - spectrum of, 233, 247, 248
- cosmic ray protons and nuclei
  - solar modulation of, 204, 205
- cosmic rays, 539–584, 639



- abundances of the elements in the cosmic rays, 543–549
- air shower technique at energies  $E \gtrsim 10^{15}$  eV, 539, 541
- antiparticles in the flux of, 543
- chemical abundances of, 34, 544–547
  - features of, 545–546
- confinement time in the Galaxy and cosmic ray clocks, 563–565
- confinement volume for, 565–568
- cosmic ray clocks
  - observed abundances of radioactive spallation products, 565, 566
  - radioactive spallation products and, 563, 564
- differential energy spectra for different species, 540–542
- differential energy spectra for electrons, 542–543
- differential energy spectrum of
  - ‘ankle’ in, 539, 540
  - ‘bump’ in, 575
  - ‘knee’ in, 539, 540, 575, 578, 629, 630, 633–635
  - overall, 539, 540
- energy density of, 390
- energy spectra of cosmic ray protons and nuclei, 33, 539–543
  - solar modulation and, 539
- energy spectrum of cosmic ray protons and nuclei, 233
- escape time  $\tau_e$  from our vicinity in the Galaxy, 563, 566
  - derived from mean spallation path length, 563
  - derived from radioactive spallation products, 565
- escape time from the Galaxy, 604
- Galactic halo, 568–571
- Greisen-Kuzmin-Zatsepin (GKZ) cut-off, 581–584
- gyroradius of, 549
- high energy electrons and the Galactic radio emission, 585, 593
- high energy protons and the Galactic  $\gamma$ -ray emission, 585
- highest energy cosmic rays and extensive air-showers, 571–573
- isotopic abundance anomalies in
  - origin of, 563
- isotopic abundances of, 547–549
  - differences from cosmic abundances, 548
- isotropy and energy density of, 549–550
- isotropy of, 566
  - as a function of energy, 549
  - Compton-Getting effect, 567
  - diffusion model for, 566–568
  - leaky box model for, 566
  - net stream of cosmic rays and, 549
  - predicted anisotropy in diffusion model, 567
  - underground muons and, 549
- isotropy of ultra-high energy cosmic rays, 578–581
- local energy density of, 550
  - compared with other local energy densities, 550
- mean free path for scattering in the interstellar medium, 567
- mean spallation path length of  $50 \text{ kg m}^{-2}$ , 565
- observation of the highest energy, 573–578
- origin of the light elements in, 554–563
  - abundance differences compared with cosmic abundances, 554
- overall statistics for, 539
- particle detectors in space observatories, 539
- residence time in the Galaxy, 579
  - dependence upon particle energy, 579
- Solar System abundances of the elements, 543–545
- source abundances compared with the local Galactic abundances, 558–560
  - correlation with first ionisation potential, 560
  - first ionisation potential and, 558
- streaming instability due to excitation of Alfvén and hydromagnetic waves, 567
- transfer equation for light nuclei, 554–561
- ultra-high energy, 34
  - anisotropies in distribution of, 34
  - cutoff at very high energies, 34
- variations in the chemical composition of cosmic rays with energy, 561–563
  - boron-to-carbon ratio, 561, 562
  - chromium-to-iron ratio, 561, 562
- cosmic rays and the discovery of new particles, 31–32
- charged and neutral kaons, 32
- mesotron, 32
- muon, 32
- pion, 32



- positron, 32
- strange particles, 32
- cosmic rays in the atmosphere, 321–326
  - electromagnetic cascades, 321–323
  - formation rate and half-life of  $^{14}\text{C}$ , 324
  - formation rate and half-life of  $^3\text{H}$ , 325
  - nucleonic cascades, 321–323
  - path-length for nuclear interaction, 323
  - pion production, 321–323
  - radioactive nuclei produced by cosmic rays
    - in the atmosphere, 324–326
    - formation of carbon-14  $^{14}\text{C}$ , 324
    - formation of tritium  $^3\text{H}$ , 324
    - residence time in atmosphere, 325
  - secondary fluxes of relativistic electrons, 323
  - vertical fluxes of, 324
  - vertical fluxes of at different heights, 323
- cosmic rays, solar
  - underabundances correlated with first ionisation potential, 559
- cosmic star formation rate
  - maximum at redshifts  $z \sim 1 - 2$ , 819
  - problem of dust extinction, 815
  - submillimetre determinations of
    - as a function of redshift, 816
- cosmic web, 111, 112
- Cosmic-Ray Isotope Spectrometer (CRIS) of the Advanced Composition Explorer (ACE), 565, 566
- cosmological aspects of high energy astrophysics, 781–823
- cosmological distance ladder, 831, 832
- Coulomb's law of electrostatics, 172
  - relativistic transformation of, 149–151
- counts of active galaxies
  - evolution in infrared waveband, 809
- counts of extragalactic radio sources, 787–789
  - excess of faint radio sources, 787
    - evidence for strong cosmological evolution, 789
- counts of galaxies, 800–807
  - excess of faint blue galaxies, 801, 804
  - and starburst galaxies, 806
  - nature of, 805–807
  - fluctuations in, due to large-scale clustering, 800, 803, 804
  - for irregular/peculiar/merger systems, 805
  - for spheroidal and spiral galaxies, 805
  - in infrared K-waveband, 804, 806
  - in U, B, R, I and K wavebands, 803
  - problems of determining, 800–804
- counts of galaxies and active galaxies, predicted, 783–793
  - at submillimetre wavelengths, 810–812
    - normalised differential counts, 810, 811
  - Euclidean, 783
    - differential, 783
    - integral, 783
  - for standard world models, 783–800
    - for sources with power-law spectra, 783–784
    - infrared counts for galaxies, 798–800
    - normalised, differential, 783–784
    - optical counts for galaxies, 798–800
    - slopes of integral and differential, 784
- counts of infrared and submillimetre sources
  - convergence of, at mid-infrared wavelengths, 810
- IRAS galaxies
  - excess of faint sources, 807
- Spitzer Survey
  - excess of faint sources, 807
  - submillimetre wavelengths, 812
    - excess of faint sources, 812
- counts of mid and far-infrared sources, 810
- counts of radio quiet quasars, 646, 647, 792
- counts of submillimetre sources, 810–813
- counts of X-ray sources, 794–798
  - evidence for evolution of the source populations, 794
  - hard X-ray energies, 2 – 10 keV, 657, 794, 796
  - history of, 794
  - problems of interpretation, 794
  - soft X-ray energies, 0.5 – 2 keV, 794, 796
    - and the integrated X-ray background emission, 794
- Crab Nebula (M1, NGC 1952), 25, 26, 28, 213, 414, 447, 599, 640, 705, 770
  - continuous injection of energy into, 448
  - energy requirements of, 448
  - pulsar in, 414, 444, 447, 448, 456, 457, 461, 463, 465, 467
- critical density for degenerate gas, 433
- critical angular frequency for synchrotron radiation, 229, 230
- critical brightness temperature, 289, 290
- critical cosmological density, 140
  - in neutrinos with finite mass, 138
- critical density

- for common ions, 373, 375
- critical density for stabilisation in degenerate neutron gas, 440
- critical density for star formation, 820
- critical Fermi momentum  $p_F$ , 440
- critical frequency for synchrotron radiation, 222, 232–234, 240, 245
- crossing time, 118
- crossing time  $\tau_{cr}$  of star or galaxy in a cluster, 166, 167
- Cryogenic Dark Matter Search (CDMS II), 140
- current sheets, 354
- curvature of space-time in general relativity, 470
- curvature radiation, 222, 468
- cusp catatrophe, 133
- cyclotron absorption features, 443
- cyclotron absorption features in accreting X-ray sources, 217–219
  - magnetic field estimates from, 218
- cyclotron absorption features in isolated neutron star, 218
- cyclotron absorption features in isolated neutron stars
  - magnetic field estimates from, 219
- cyclotron radiation, 216–219
  - broadening of spectral lines of, 217
  - circular polarisation of, 217, 218
    - geometry of magnetic field configuration and, 218
  - magnetic field estimates from, 218
  - harmonics of gyrofrequency, 216, 217
  - mildly relativistic, 216
- cyclotron radius of charged particle in magnetic field, 196
- Cygnus A, 26, 288, 534, 603, 640, 702–707, 723–725, 727, 731–734, 736, 747, 848
  - abnormally nearby, 702
  - absence of internal depolarisation, 735
  - intergalactic magnetic flux density in surrounding intracluster gas, 735
  - mass of associated cluster and intracluster gas, 735
  - minimum energy requirements for, 603
  - optical spectrum of, 702–707
    - comparison of theoretical and observed spectrum, 703
    - comparison with the spectrum of the Crab nebula, 705
    - estimates the element abundances in emitting line regions, 705
    - estimates the temperatures and densities of emitting line regions, 705
    - influence of dust extinction on, 703
    - origin of continuum radiation, 705
    - origin of dust extinction in, 703
    - other Type 2 systems and, 707
    - photoionisation models for, 705
    - physical properties of the clouds responsible for, 705, 706
    - wide range of ionisation states in, 703
  - rotation measure distribution, 735
  - shocks and cooling flows in surrounding intracluster gas, 735
  - typical of luminous FR2 radio sources, 735
- D galaxies, 641, 651
- damping of Alfvén and hydromagnetic waves, 567
- dark energy, 417
- dark matter, 135–140
  - astrophysical and experimental limits, 139–140
  - axions and, 138
  - baryonic, 135–138
  - black holes and, 136
    - limits to mass density from gravitational lensing, 136
  - brown dwarfs and baryonic, 136
  - forms of, 135–140
  - in clusters of galaxies, 109, 119, 121
  - in early type galaxies, 135
  - in galaxies, 85
  - MACHOs and, 138
    - gravitational microlensing and, 136
  - masses of dark matter particles, 140
  - neutrinos with finite rest mass and, 138
  - non-baryonic, 138–139
  - searches for dark matter particles, 140
  - structure of, 133
  - WIMPs and, 138
- dark matter haloes of galaxies and clusters, 133
- Davis–Greenstein alignment mechanism, 407
- de Broglie wavelength, 307
- de Vaucouleurs  $r^{1/4}$  law for surface brightness, 91, 116
- dead stars, 413–482
- Debye length, 327–329, 331, 486, 615
  - as shielding distance in plasma, 328, 329

- decay of binary orbits and gravitational waves, 35
- declination (Dec or  $\delta$ ), 825, 826
- deflagrations, 419
- degeneracy pressure, 431
  - condition for use of relativistic equation of state, 433, 434
  - conditions under which important, 431, 433, 434
- degenerate gas
  - non-relativistic equation of state for, 432, 433
  - relativistic equation of state for, 433
    - of electrons, 433
    - of neutrons, 434
- degenerate stars
  - internal structure of, 431–434
- dendrochronology, *see* tree-ring-dating
- density wave theory of spiral structure, 388, 504
  - forcing mechanisms and, 389
- dentist's drill model for jets in FR2 radio sources, 742
- depolarisation of polarised radio signals, *see* Faraday depolarisation
- detection of ultra-high energy  $\gamma$ -rays, 292
- detonations, 419
- deuterium formation in stars, 49, 60
  - neutrinos from, 49
- diagnostic diagram
  - alignment effect and, 717
- diagnostic diagram for emission line galaxies, 706, 707
  - distinguishing photoionisation by hot stars from non-thermal radiation, 707
- differential rotation of Galactic disc, 387
- diffraction optics, 838
- diffraction-limited telescopes, 838–845
- diffusion coefficient  $D$ , scalar, 208
- diffusion coefficients for high energy particles in fluctuations in magnetic field, 204
  - physical model for, 204–205
- diffusion of charged particles, 329–332
  - mean free path and, 330
- diffusion time for magnetic field in a plasma, 340, 342, 355
- diffusion-loss equation, 278, 586, 594, 608
  - escape time, 278
  - including radioactive decay, 564–565
    - solution of, 564
  - including term for diffusion of particles in momentum space, 620
  - source term, 278
  - statistical acceleration and, 277
  - steady-state solutions for particle acceleration, 618
- diffusion-loss equation for high energy electrons, 590–594
- distortions of the injection energy spectrum, 590–591
- steady-state solutions for, 590–591
  - under synchrotron and inverse Compton losses, 591, 592
- time evolution
  - under synchrotron and inverse Compton losses, 591, 592
- diffusion-loss equation for high energy particles, 207–211
  - coordinate-space approach, 209–211
  - elementary approach, 208–209
    - including spallation gains and losses, catastrophic loss of particles, radioactive decay, 210
- diffusive shock acceleration, 621–635, 730
  - advection of particles from shock acceleration region, 625
  - average energy gain on crossing shock wave, 624
  - average energy gain per cycle of acceleration, 625
  - box-model of, 626
  - differential power-law energy spectrum from, 625
  - efficiency of conversion of kinetic energy to particle energy, 628, 633
  - first-order Fermi acceleration, 622
  - for shock waves with different compression ratios, 627, 631
  - fraction of particles lost per cycle, 625
  - non-linear features of, 628
  - overcoming the adiabatic loss problem, 627
  - scattering by Alfvén and hydromagnetic waves, 626
  - scattering by streaming instabilities or turbulent motions, 622, 623
  - symmetry of acceleration process in crossing of shock front, 624
  - upper limit to particle energy, 626
- diffusive shock acceleration in strong shocks, 616
- diffusive velocity, 357

- dimensional analysis, 606
- dipole radiation, 173, 220, 221
- Dirac  $\delta$ -function, 176, 181, 329
  - Fourier transform of, 181
- dispersion measure, 459
- dispersion measure of pulsars, 375–377
- dispersion prism, or grating, 645
- displacement four-vector  $R$ , 149, 169, 170, 856
- dissipation time-scale, 355
- distance indicators, 830
  - problems of using, 830
- distance measure  $D$ , 784
- distances in astronomy, 10, 829–832
  - astrophysical methods, 830, 832
  - Baade-Wesselink method, 830
  - gravitational lenses, 832
  - Sunyaev-Zeldovich effect, 831
  - using distance indicators, 830
- distribution of mass in clusters
  - bremsstrahlung X-ray emission and, 671
- Doppler shift formula, relativistic, 262
- Dreicer field, 615
- ‘drop-out’ galaxies, 806, 814
- Drude model, *see* electrical conductivity of a fully ionised plasma, Drude model for
- Drury instability, 629
- dust, *see* interstellar dust
  - sublimation temperature of, 714
- dust emission in millimetre and submillimetre waveband, 17
- dust extinction of galaxy spectral energy distribution, 807, 809
- dust shells about giant stars, 83
- dwarf novae, *see* cataclysmic variables, dwarf novae
- dynamical friction, 143, 165–167, 678
  - clusters of galaxies and, 167
  - galaxies and, 167
  - globular clusters and, 167
  - limits to collision parameters and, 166
  - regular clusters of galaxies and, 167
- dynamical timescale of a star, 46
- dynamics of a charged particle in a magnetic field
  - with small scale fluctuations, 203
- early-type galaxies, 87, 89
  - mass distribution in, 135
- Earth’s magnetosphere, *see* magnetosphere of Earth
- eclipsing X-ray binary with stellar mass black hole, 481
- eddies, turbulent, 496
- Eddington limiting luminosity, 79, 452, 486–488, 490, 491, 495, 502–504, 511, 512, 515, 521, 527, 535, 669, 670, 693, 696, 718, 720, 721, 734
- effective aperture of an antenna, 849, 854
- effective temperature  $T_{\text{eff}}$ , 39, 53
- effective temperature of relativistic gas, 240
- Effelsberg 100-m radio telescope, 404, 569, 677
- EGRET source catalogue in Galactic coordinates, 766
- 8-10 metre optical-infrared telescopes, 7
- Einstein angle, 130, 133
- Einstein coefficients for spontaneous and stimulated emission and stimulated absorption, 187, 242
  - relations between, 274
- Einstein radius, 130, 133
- Einstein ring, 129–131
- Einstein X-ray Observatory, 27, 78, 123, 656
- Einstein-de Sitter world model, 800
- electric dipole moment, 172
- electrical conductivity of a fully ionised plasma, 333–334, 338, 354, 355
  - dissipation of energy and, 354
  - Drude model for, 330, 333
  - including effect of electron–electron collisions, 334
  - Lorentz approximation for, 333
- electrical conductivity of metals
  - typical values for, 334
- electromagnetic field
  - energy density of, in a medium, 294
- Electromagnetic Processes* (Gould), 141
- electromagnetic showers, 292, 299–302
  - critical energy  $E_c$  for, 300, 301
  - degradation of energy by ionisation losses at low energies, 300
  - degradation of energy through the atmosphere, 300
  - properties of, 300, 302
  - simple model for, 299
  - total number of particles with depth through a medium, 301
- electromotive force, 198, 334–336
- electron cyclotron radiation features in the X-ray spectra, 511
- electron degeneracy pressure, 76, 84, 413

- electron scattering, *see* Thomson scattering, 502, 503, 721
- electron–photon cascades, *see* electromagnetic showers
- electron–positron annihilation line from the direction of the Galactic Centre, 304, 305
- electron–positron pair production, 297–299
  - cross-section at intermediate photon energies, 297
  - cross-section in the ultrarelativistic limit, 298
  - impossibility in free space, 297
  - radiation length for, 298
  - similarity of radiation length for bremsstrahlung and for, 298, 299
- electron–positron annihilation, 302–305
  - annihilation at rest or in flight, 303
  - broadening of  $\gamma$ -ray lines, 304
  - cross-section for
    - in extreme relativistic limit, 305
    - thermal electrons and positrons, 305
  - maximum and minimum energies of photons, 304
  - of positronium atoms, 304
- electron–positron annihilation line, 318, 320
- electron–positron, or electromagnetic, cascades, 571
- electrostatic encounters between charged particles, 614
- emission from the Earth’s atmosphere  $T_{\text{atm}}$ , 854
- emissivity  $\kappa_\nu$ , 186
  - in terms of elementary atomic processes, 188
- emissivity of telescope in infrared waveband, 850
- encircled energy fraction, 842, 843
  - for circular mirror with central hole, 846
  - with varying wavefront errors, 843
- end-points of stellar evolution, 84
- energies, useful conversion formulae, 855
- energy densities in high energy particles and magnetic fields in the Galaxy
  - roughly equality of, 570, 571
- energy density of starlight in our Galaxy, 589
- energy dissipation rate by viscous forces, 498
- energy generation, 53
- energy loss processes for high energy electrons, 585–590
  - adiabatic losses, 587–588, 590, 591
  - bremsstrahlung, 586–587, 590, 591
  - inverse Compton scattering, 589–591, 593, 594
  - ionisation losses, 586, 590, 591, 593
  - maximum lifetime of high energy electrons anywhere in the Universe, 589
  - relative importance of inverse Compton scattering and synchrotron losses, 589
  - synchrotron radiation, 542, 588, 590, 591, 593, 594
  - under interstellar conditions, 590
- energy transport in stars, 50–53
- enthalpy per unit mass, 346
  - for perfect gas, 346
- entropy of plasma
  - conservation of, 338
- equation of continuity, 622
- equation of hydrostatic support, 113, 492
- equation of mass conservation, 113
- equation of state of stellar material, 44, 53, 58
- equations of stellar structure, 53–56, 435
- equidistant azimuthal polar projection, 7, 827, 828
- equipartition theorem, 672
- equivalent current loop for particle gyrating in magnetic field, 197–199
- equivalent noise temperature  $T_n$ , 852
- EROS project, 138
- escape time of high energy particles in the Galaxy, 592, 593
- ESO 3.5 m New Technology Telescope, 680
- ESO-SERC Southern Sky Survey, 110
- Euler’s constant, 184
- Euler-Lagrange equations, 689
- European VLBI network, 747
- evaporation time for a cluster of stars, 678
- Evidence for the occurrence of violent events in the nuclei of galaxies* (Burbidge, Burbidge and Sandage), 648
- evolution of active galaxies with cosmic epoch, 787–798
  - extragalactic radio sources, 787–792
    - ‘luminosity evolution’, 790
    - cut-off of strong evolution beyond redshift  $z \sim 2 - 3$ , 791, 792
    - for sources with steep and flat radio spectra, 790
    - luminosity-dependent density evolution, 791, 792
  - radio quiet quasars, 792–793

- evolution of galaxies and active galaxies with
  - cosmic epoch, 781–813
  - mid and far-infrared number counts, 807–810
- active galaxies, 782, 787–798
  - extragalactic radio sources, 787–792
  - radio quiet quasars, 792–793
  - X-ray clusters of galaxies, 798
  - X-ray sources, 794–798
- brief history of evidence for, 781–782
- co-evolution of stellar and black hole properties of galaxies, 782
- counts of galaxies, 800–807
- counts of galaxies and active galaxies, 783–793
  - euclidean source counts, 783
  - for standard world models, 800
  - predicted, for standard world models, 783–784
  - submillimetre counts of dusty galaxies, 810–812
- stellar and gaseous components of galaxies, 782
- submillimetre number counts, 810–813
- $V/V_{\text{max}}$  or luminosity-volume test, 786–787
- excess of faint blue galaxies
  - irregular nature of, 806
- exoplanets, 74–76
  - Doppler technique for discovering, 74
  - highly elliptical orbits of, 75
  - Jupiter mass planets very close to parent stars, 75
  - occultation technique for discovering, 75
  - problems of accounting for orbits of, 75
- EXOSAT X-ray telescope, 489, 523, 527
- explosive nucleosynthesis, 73
- extensive air-showers, 323, 571
- extinction
  - role of absorption and scattering, 378–381
- extinction by interstellar dust grains, 8, 10
  - extinction coefficient, 10
- extinction curves, 378
- extinction efficiency  $Q$ , 380, 381
- extragalactic radio sources, 723–744
  - astrophysics of FR2 radio sources, 730–738
  - energetics and energy densities, 731–733
  - gas dynamics of FR2 radio sources, 736–737
  - synchrotron losses and time-scales, 733–735
  - synchrotron radiation and, 730–735
  - young FR2 radio sources, 737–738
- extended radio sources – Fanaroff-Riley types, 662, 723–729
- extended sources
  - Fanaroff-Riley types, *see also* Fanaroff-Riley Type 1 (FR1) and Type 2 (FR2) radio sources
- FR1 radio sources, 740
- jet physics, 742–744
  - electromagnetic processes in black holes and, 742, 743
  - gas dynamical processes and, 743
  - magnetic instabilities and, 743
  - rotation of black holes and, 742
  - twin-exhaust model for, 743, 744
- luminosity function of
  - evolution with cosmic epoch, 789–792
- microquasars, 740–742
- properties of, 723–729
  - classical double radio sources, 727
  - compact nuclear radio sources, 723, 725
  - hot spots, 723, 725
  - members of rich clusters of galaxies, 725
  - radio jets, 723
  - radio lobes of, 723
  - radio-trail radio sources, 727
  - self-similar structure of FR2 radio sources, 725
  - spectra of, 723
  - surrounded by hot intergalactic gas, 723, 725
- radio emission of spiral galaxies, 728
- radio emission of starburst galaxies, 728
- radio luminosity function of, at present epoch, 728, 729
- relativistic jets in, 723
- Extreme Ultraviolet Explorer (EUVE), 24
- Faber-Jackson relation and fundamental plane, 96–97
  - and the distances of galaxies, 97
- Fanaroff-Riley Classes, 729
  - dividing radio luminosity as a function of absolute optical magnitude of host galaxy, 728
  - radio luminosities of Types 1 and 2, 727, 728
- Fanaroff-Riley Type 1 (FR1) radio sources, 726, 727, 738–740
  - asymmetric structures on small scales, 739
  - deceleration of relativistic beams in cores of, 739, 740, 758

- relativistic beaming in cores of, 739
- relativistic motions in, 757
- role of buoyancy in, 738
- X-ray images of cavities inflated by buoyancy, 739
- Fanaroff-Riley Type 2 (FR2) radio sources, 727, 730–738
  - astrophysics of, 730–738
  - compact symmetric objects (CSO), 731
  - deviations from symmetry, 757
  - energetics and energy densities, 731–733
    - Cygnus A, 731–733
    - equipartition magnetic fields in Cygnus A, 731–733
    - minimum energy requirements for synchrotron radiation, 731
    - minimum pressures in Cygnus A, 732
    - pressure of hot intracluster gas, 732
    - synchro-Compton radiation from hot-spots in Cygnus A, 732
  - formation of cocoon in, 730
  - formation of hot-spots in, 730
  - schematic models for, 730, 731, 735, 736
  - self-collimation of jets in, 731
  - synchrotron losses and time-scales, 733–735
    - continuous energy supply, 734
    - in Cygnus A, 733
    - particle acceleration in hot-spots of Cygnus A, 734
    - rate of supply of energy, 734
    - speed of advance of hot-spots, 734
    - variation of spectral index in Cygnus A, 733, 734
- Faraday depolarisation, 377–378
- Faraday rotation of linearly polarised radio signals, 376–378, 402–404
  - direction of magnetic field and, 377
  - estimates of the Galactic magnetic field and, 377
  - refractive indices of elliptically polarised waves, 376
  - right- and left-handed elliptically polarised waves, 376
  - rotation measure, 377
- feedback processes and the masses of giant elliptical galaxies, 685
- Fermi acceleration - original version, 616–622, 624, 626
  - as a second-order process, 618
  - average energy gain per collision, 618
  - average rate of energy gain, 618
  - broadening of energy spectrum by random collisions, 620
  - characteristic loss time  $\tau_{\text{esc}}$  from acceleration region, 616
  - exponential increase in energy, 618
  - formation of a power-law energy spectrum, 619
  - head-on and following collisions, 617
    - probabilities of, 617
  - injection problem, 619
  - ionisation losses and, 619
  - magnetic mirrors and, 616
  - modern version including interactions with plasma waves, 621
  - problems with, 619–620
    - injection problem, 619
    - ionisation losses and, 619
    - slow increase in energy of particles, 619
    - why a standard power spectrum?, 619, 620
  - random scattering between cloud collisions, 617
  - relation between mean square energy change and increase in energy per collision, 621
  - second order Fermi acceleration, 622
  - stochastic energy gains and, 616
- Fermi energy, 440
- Fermi Gamma-ray Space Telescope, 765, 769, 773
  - Large Area Telescope Bright Active Galactic Nuclei (AGN) Sample (LBAS), 765
- Fermi Large Area Telescope, 766
- Fermi momentum of a degenerate Fermi gas, 433
- Fermi-Dirac distribution, 433
- Fermi-Thomas model of the atom, 190
- filling factor, 372
- fine structure constant, 147, 183, 252, 438
- Finkelstein coordinates, 473
- firehose instability, 629
- first adiabatic invariant, 199
- first point in Aries, 825
- first-order Fermi acceleration, *see* diffusive shock acceleration in strong shocks
- fluctuations in black body radiation, 852, 853
- fluctuations in the Cosmic Microwave Background Radiation, 820
- Fluid mechanics* (Landau and Lifshitz), 344
- fluorescent X-ray lines, 686–688



- physics of, 686–687
- tracers of velocity field in accretion discs, 687
- flux densities, luminosity, magnitudes and colours in astronomy, 833–837
- flux density, 834
  - bolometric, 834, 836
  - definition of, 833
- Fokker–Planck equation for stars in clusters, 116
- Fokker–Planck equation for the diffusion of the particles in momentum space, 620, 622, 627
- fold catastrophe, 133
- forbidden transitions in spectra of gaseous nebulae, 372–375
  - critical density for, 375
  - metastable energy levels and, 374
  - radiative de-excitation and, 374
- Formation of Stars, The* (Stahler and Palla), 393
- 48-inch Schmidt Telescope Palomar Sky Survey (POSS), 109
- four-dimensional momentum space
  - volume element of as a Lorentz invariant, 274
- Fourier analysis, 845–848
  - addition theorem, 845
  - convolution theorem, 846
- Fourier transformation, 178, 179, 203, 221–223, 232
- Fraunhofer diffraction, 839
  - for circular aperture, 840–842
    - encircled energy fraction, 843
  - for circular mirror or lens, 840
  - for rectangular slit, 839
  - for single slit, 839
- free-fall velocity in general relativity, 471
- free-free emission, *see* bremsstrahlung
- frequencies of galaxies of different types, 803
  - in different galactic environments, 800
- frequency four-vector  $\mathbf{K}$ , 752, 857
- fully convective stars
  - stability criterion for, 66
- fundamental plane, 96–97
- Galactic Astronomy* (Binney and Merrifield), 86
- Galactic Centre, 8, 679, 826, 828
  - black hole in nucleus of, 678–681
  - mass density close to, 680, 681
  - mass of, 680, 681
  - infrared flares in, 681
  - mass distribution in, 680, 681
  - optical extinction to, 678
  - orbit of star S2 about, 680, 681
  - orbits of stars about, 679
  - supermassive black hole in, 13
- galactic coordinates, 826, 827
- Galactic Dynamics* (Binney and Tremaine), 86
- galactic equator, 826, 827
- Galactic halo, 568–571
  - galactic fountains and, 569
  - observed in UV absorption lines of CIV and SiIV, 568
  - radio, 568
- galactic latitude ( $b$ ), 826
- galactic longitude ( $l$ ), 826, 828
- Galactic magnetic field, 248, 402–411
  - aligned with local spiral arm, 407
  - Faraday rotation in the interstellar medium, 402–404
  - large fluctuations in, 402, 403
  - large-scale order in, 402, 403, 407
  - magnetic flux density from pulsar rotation measures, 249
  - mean magnetic flux density, 411
  - North Polar Spur and, 407
  - optical polarisation of starlight, 404–407
  - radio emission of spinning dust grains and, 408–410
  - radio emission of the Galaxy and, 411
  - summary of the information on, 411
  - Zeeman splitting of 21-cm line radiation and, 410
- galactic north pole, 826–828
- Galactic radio emission
  - spectrum of, 593
    - break in, 593, 594
    - variations with location in Galaxy, 594
- galactic south pole, 827, 828
- galaxies, 85
  - barred spiral SB, 86
  - collisions between, 88
  - colour-luminosity relation for elliptical galaxies, 97
  - correlations among the properties of, 95–98
  - Faber–Jackson relation and fundamental plane, 96–97



- mass-metallicity relation for galaxies, 97–98
- Tully-Fisher relation for spiral galaxies, 96
- elliptical E, 86
  - ellipticities of, 86
- gas phase metallicity-luminosity relation for late-type galaxies, 98
- Hubble sequence, 86–88
- interactions between, 109
- irregular, 86
- large-scale distribution of
  - holes and voids in, 111
  - sheets and filaments in, 111
- lenticular or S0, 87
- mass-metallicity relation for galaxies, 98
- masses of, 98
- normal spiral S, 86
- old red, *see* old red galaxies
- passive evolution of, 799
  - importance of red giant branch, 798
- peculiar, 88
- red and blue sequences, 89–95
- ring, 88
- statistics of galaxies belonging to red and blue sequences, 95
- surface brightness distributions of, 91, 94
  - discs, 91, 92
  - spheroids or bulges, 91, 92
- ‘tuning fork’ diagram for, 86
- Galaxies in the Universe: an Introduction* (Sparke and Gallagher), 86
- Galaxy
  - dark matter in, 387
  - mass of, 832
  - radio emission of, 246–249
    - radio disc, 247
    - thickness of radio disc, 248
  - rotation curve of, 387
- galaxy downsizing, 685
- Galaxy Formation* (Longair), ii, iii, 86, 111, 130, 140, 682, 832
- galaxy formation
  - collisions between galaxies and, 819
  - ‘down-sizing’, 819
  - feedback mechanisms and, 819
  - growth of supermassive black holes and, 819
- Lyman-break galaxies
  - multicolour technique for discovering, 813
- observed global star formation rate, 813–816
  - star-forming galaxies and, 813
  - starburst galaxies at large redshift, 813
  - star and element formation and, 813–816
  - star formation and, 819
- GALLEX solar neutrino experiment, 34, 63
- $\gamma$ -ray background emission
  - Comptonisation and, 798
  - spectrum of, 794
- $\gamma$ -ray bursts, 28, 419, 771–780
  - afterglows
    - discovery of, 773
    - prediction of, 771
  - afterglows of long and short bursts, 775
  - anisotropy of emission, 778
  - at very large redshifts, 773
  - bimodal distribution of burst durations, 771, 772, 775
    - host galaxies of long and short bursts, 775
  - cartoons of evolution of, 779
  - causality arguments and size of emission regions, 776
  - collapsar model for, 780
  - compactness parameter, 776
    - relativistic beaming and, 777
  - discovery of, 771–773
  - energy releases of, 774
  - evolution of X-ray afterglows, 775, 776
  - extragalactic origin of, 773
  - isotropy of distribution on sky, 771, 772
  - long, 771–774
    - association with core-collapse supernovae, 775, 779, 780
    - relativistic beaming factors for, 780
    - time-lag for, 775
    - Wolf-Rayet stars and, 780
- number counts of, 771
- physics of, 776–780
- probes of the reionisation era, 773
- properties of, 774–776
- relativistic bulk motion and, 776
- relativistic fire-ball model for, 776–777
  - first-order Fermi acceleration in, 777
  - relativistic shock waves in, 777
- relativistic jets
  - break in afterglow light-curve, 779
  - deficiencies of the standard models of, 779
  - energetics of models of, 779

- evolution of, 778
  - short, 771–774
    - correlation with regions of low star formation, 775
    - gravitational waves and, 780
    - merger of compact binaries and, 780
    - spectra of long and short bursts, 775
    - supernova association, 773
    - time evolution of synchrotron radiation sources and, 777, 778
- $\gamma$ -ray Cherenkov telescopes, 770
- $\gamma$ -ray observations of the Galaxy, 539, 550–554
  - distribution of cosmic rays in the Galaxy and, 550–554
  - luminosity of, 552
  - pion production and, 551
    - cross-section for, 551
  - relativistic bremsstrahlung of ultrarelativistic electrons, 552, 553
  - spectrum of  $\gamma$ -rays produced by inverse Compton scattering of starlight, 552–554
  - spectrum of  $\gamma$ -rays produced from neutral pion decay, 551, 552
- $\gamma$ -ray sources in active galactic nuclei, 764–771
  - association with blazars and superluminal sources, 653
  - compactness parameter and, 767–768, 770
    - relativistic beaming and, 768
  - distribution of point  $\gamma$ -ray sources, 764–765
  - energy densities of radiation in, 767
  - extreme variability of, 770
  - $\gamma$ -ray photosphere, 767, 768
  - hyperluminous, 669
  - inverse Compton scattering and, 768
  - luminosities of, 766
  - photon-photon collisions in, 767–768
  - relativistic beaming factor for, 769, 770
  - relativistic jet models for, 768–771
  - superluminal sources and, 765
  - synchro-self Compton models for, 769
  - TeV sources, 770
  - types of object associated with, 765, 766
  - variability of, 766, 767
- $\gamma$ -ray waveband, 27–29, 551
  - $\gamma$ -ray line emission, 28
  - Cherenkov detection technique, 29
  - detectors for, 28
- gas dynamics of FR2 radio sources
  - contact discontinuity and shock structure in, 736
  - ram pressure and, 736
  - role of cocoon in stabilising jets, 736, 737
  - self-similar solutions and, 736
  - speed of advance of hot-spots, 736
  - waste energy problem and, 736
- gauge selection in electrodynamics, 175
- Gaunt factors, 121, 123, 184, 331, 334
  - bremsstrahlung, 586
  - for diffusion of particles in a plasma, 332
  - for electrical conductivity of plasma, 332
  - frequency averaged, 185
- Gauss's theorem for Newtonian gravity, 131
- Gaussian point-spread function, 844
- Gemini Deep Deep Survey, 817, 818
- Gemini North telescope, 480
- general relativity, 469–473
  - conservation of angular momentum, 689
  - dynamics of particles about point mass, 471
  - radial motion of test particle in, 689
- GEO600 gravitational wave experiment, 36
- geodesic distance, 470
- giant branch, 41, 43, 44, 55, 69, 77, 81, 82
- giant molecular clouds, 341, 396–398
  - formation of, 388
    - in spiral density waves, 389
  - percolation processes and, 389
  - supernova explosions and, 389
- gigahertz peaked spectrum objects (GPS), 747
- Ginga X-ray observatory, 660
- globular clusters, 44, 76
  - oldest, 77
  - typical parameters for, 167
- Goldstake solar neutrino experiment, 34
- GOLF experiment of the ESA SOHO mission, 58, 59
- Gran Sasso Laboratory, in Central Italy, 63
- grating telescope, 848
- gravitational deflection of light rays, 132, 133
  - by the Sun, 129
    - collision parameter for, 129
- gravitational fine structure constant, 438
- gravitational lensing, 109, 832
  - strong, 135
  - weak, 133
- gravitational lensing by galaxies and clusters
  - of galaxies, 129–135
    - caustics and cusps in, 133
    - cluster masses from, 133
    - critical surface density for, 132

- distortion of background images by, 133
- galaxy-galaxy imaging and, 135
- necessary conditions for, 131
- Gravitational Lensing: Strong, Weak and Micro* (Schneider, Kochanek and Wambsganss), 131
- gravitational redshift, 667, 688, 689, 691, 692
- gravitational relaxation time  $\tau_r$ , 165–167
- grazing incidence optics, 23, 25
- Great Observatories Origins Deep Survey (GOODS), 802, 803, 815
- grey-body spectrum, 807, 809
- Grotrian diagram, 374
- group velocity, 375
- guiding centre, 214, 229
- guiding centre motion, 197, 199, 203, 204
- gyration radius of cosmic ray protons in magnetic field, 549
- gyrofrequency, 196, 375, 376
  - non-relativistic, 197, 216, 222, 229, 230, 746
  - relativistic, 213, 216, 222, 232, 236
- gyroradius, 203
  - and rigidity  $R$ , 204
  - charged particle in magnetic field, 196
- gyroscopic precession about rotating black holes, 475
  
- Hammer-Aitoff projection, 8, 9, 12, 14, 16, 19, 24, 29, 828
- Handbook of Space Astronomy and Astrophysics* (Zombeck), 141
- hard low mass X-ray binary stars, 304, 305
- Harvard spectral classification system, 41, 42
  - spectra of main sequence stars in, 42
- Hawking radiation, 478
- Hayashi tracks, 66–69, 71
  - for fully convective stars, 67
- HEAO-1 X-ray Observatory, 794
- HEAO-A2 experiment, 185
- HEAO-C satellite, 28
- HEAO-C2 cosmic ray experiment, 545
- HEAO-C3 cosmic ray experiment, 546, 547
- heat diffusion equation, 50
- Heisenberg's uncertainty principle, 147, 152, 307, 369, 431–433
- helioseismology, 56–60
  - acoustic or  $p$ -modes, 58
  - gravity or  $g$ -modes, 58
  - probing the structure of the Sun and, 58–60
- helium
  - primordial nucleosynthesis of, 60
  - cosmic abundance of, 43
- helium burning, 71, 81
- helium flash, 81, 438
- helium shell burning, 71
- Herbig-Haro (HH) objects, 398, 399
- Hercules X-1 (Her X-1), 218, 443, 450, 451
  - discovery records of, 451
  - modulation of light curve, 527
  - precession of rotation axis of neutron star, 527
  - unpinning of crust and magnetic field from neutron superfluid, 527
- Hertzsprung-Russell diagram, 39–44, 55, 66, 70, 71, 73, 76–78, 81–83
  - for clusters of stars, 42
  - for white dwarfs, 439
  - theorist's, 76, 77
- HESS Cherenkov  $\gamma$ -ray telescope array, 29, 597, 769, 770
- Hess ultra  $\gamma$ -radiation, 30
- HETE-2 satellite, 773
- hierarchical models of galaxy formation
  - old red galaxies and, 818
- High Energy Astrophysics* (Longair), ii
- high energy astrophysics
  - definition of, 3
  - modern physics and astronomy and, 3–5
- high energy electron energy spectrum in the local interstellar medium, 592–594
- high-mass X-ray binaries, 529–531
  - capture, or accretion, radius for stellar wind, 529, 530
  - O and B stars in, 529
  - properties of, 529
  - X-ray luminosity due to accretion, 530
- highest energy cosmic rays, 571–584
  - charges and masses of, 636
  - chemical composition of, 576–578, 580
  - correlation with nearby galaxies and active galaxies, 579–581
  - Cosmic Microwave Background Radiation and, 574, 581, 583
  - cut-off due to photonuclear interactions for nuclei, 583–584
  - Monte Carlo calculations for, 584
  - depth through atmosphere of maximum shower development  $X_{\max}$ , 571, 576–578
  - detection by emission of fluorescent radiation, 572
  - differential energy spectrum of, 573–578

- distortion of spectrum due to photo-pair production, 582, 583
  - fly's eye telescopes, 572
  - Gaisser-Hillas function, 572, 576
  - Greisen-Kuzmin-Zatsepin (GKZ) cut-off, 581–584
    - at  $5 \times 10^{19}$  eV for protons, 581
  - gyroradius of, 578–580
    - protons and iron nuclei, 579
  - high energy neutrino production and, 581
  - HiRes experiments, 572, 575–578, 582–584, 635
  - largest measured energies, 573
  - maximum distance from which they originated for protons, 581
  - modification factor for, 582, 583
  - photo-pair production dip, 582
  - Pierre Auger Observatory, 572, 573, 575–580, 583, 584
  - potential sites for acceleration of, 635, 636
  - scattering of, by magnetic irregularities, 579
  - slant path length, 571, 572, 576
  - spread in depth through atmosphere of maximum shower development  $\text{RMS}(X_{\text{max}})$ , 576–578, 584
  - superposition principle, 577
  - upper limit to particle energy, 635
  - Hipparcos* astrometric satellite, 40, 830
  - Homestake gold-mine, South Dakota, 61
  - homologous stellar models, 53–54, 76
    - energy generation rates, 53
    - inadequacies of, 54
  - horizontal branch, 43, 44, 77, 81
    - evolution of stars on, 81
    - mass loss and, 43
  - hot gas in clusters of galaxies
    - absence of cool gas in, 124
      - associated with heating by radio lobes, 124
    - models to explain the, 124
  - abundance of iron, 122
  - characteristic cooling time for, 123
  - cooling flows and, 123–125
    - mass inflow rates of, 123
  - cooling time of, 123
  - distribution of, 119–125
  - iron line FeXXVI from, 119
  - sound waves in, 125
- HR diagram for stars, *see* Hertzsprung-Russell diagram
- Hubble Deep Field, 781, 801, 805, 806, 813
- Hubble sequence of galaxies, 85–88, 95
  - correlations along, 95–98
    - luminosity function of HII regions, 96
    - neutral hydrogen, 95
    - star formation rates and, 96
    - total surface density and surface density of neutral hydrogen, 95
- Hubble Space Telescope, 21, 79, 82, 87, 131, 135, 398, 414, 421, 429, 430, 632, 655, 660, 673–675, 716, 725, 758, 773, 781, 801, 804, 843, 845, 846, 851
  - Wide Field Camera of, 758
- Hubble Ultra Deep Field (HUDF), 781, 801–803, 806, 813–815, 834
- Hubble's constant, 832
  - from Sunyaev-Zeldovich effect, 129
- Hubble Space Telescope Key project, 832
- measured from power spectrum of fluctuations in Cosmic Microwave Background Radiation, 832
- Huygen's principle, 838
- Huygens' construction, 292, 293, 296
- Hydrodynamics* (Lamb), 57
- hydrogen
  - ionisation potential of, 47
- hydrogen recombination lines from warm component of the interstellar gas, 372
- hydrogen recombination lines in gaseous nebulae, 372–373
  - H $\beta$  line of the Balmer series, 372
  - very high order transitions, 372–373
- hydrogen shell burning, 71
- hydromagnetic waves, circularly polarised, 206
- hydrostatic equilibrium, 43, 53, 119, 120
- hydrostatic support, equation of, 45, 671
- IMB solar neutrino experiment, 35
- IMP-7 mission, 565
- IMP-8 mission, 565
- impedance of free space  $Z_0$ , 173
- Infrared Astronomical Satellite (IRAS), 11, 13, 83
- infrared cirrus, 14
- infrared luminosity function of galaxies
  - evolution of, 807, 809
- Infrared Space Observatory (ISO), 807
- infrared waveband, 10–14
  - all-sky images in, 12–14
  - emission by dust grains at thermal infrared wavelengths, 13
  - near infrared wavelengths in, 11

- observing in, 10–11
- thermal infrared wavelengths in, 11
- wavelength windows in, 11
- initial mass function for stars, 393–396
  - Miller and Scalo, 394
  - Salpeter, 394
- inner Lagrangian point, 507, 509–511, 517, 525, 531
- instability strip, 81
- instantaneous rest frame, 173
- INTEGRAL  $\gamma$ -ray observatory, 28, 218, 282, 304, 305, 316, 317, 320
- intensity of radiation  $I_\nu$ , 186
  - definition of, 833
- interactions of high energy photons, 251–305
- intercloud medium, 372
- intercombination lines, 374
- interferometer
  - eight-element
    - power polar diagram of, 847
  - four-element
    - power polar diagram of, 847, 848
  - grating telescope, 847, 848
  - two-element, 846
    - power polar diagram of, 847
- interferometry and synthesis imaging, 845–848
- internal energy per unit mass, 346
- International Linear Collider (ILC), 139
- International Ultraviolet Explorer (IUE), 23, 78, 369, 430, 650, 699, 709, 711
- interplanetary magnetic field, 332
- interstellar chemistry, 22, 158, 368
- interstellar dust, 378–386
  - 217.5 nm absorption feature, 381
    - associated with  $\pi \rightarrow \pi^*$  transitions, 381
  - condensed matter physics of, 406
  - cross-section for scattering and absorption, 381
  - diffuse interstellar bands and, 379, 381
  - electric charging of, 406
    - coupling of grains and neutral particles through, 406
  - electric dipole moments of, 409
  - emissivity of heated, 383
  - extinction law for, 378–379
  - formation of interstellar molecules and, 381
  - graphite grains and, 381
  - heavy elements in the interstellar medium and, 378
  - Mie theory of scattering and absorption, 380, 381
  - obscuration in our Galaxy and, 378
  - optical depth for, 378
  - ratio of total to selective absorption  $R_V$ , 379
  - reddening, 379
  - reradiation of heated, 383
    - star formation and, 383
  - rotation frequency–grain radius relation
    - for different phases of the interstellar medium, 408, 409
  - rotation speed of dust grains, 405–406, 409
  - rotation speed of PAH molecules, 409
  - selective absorption, 379
  - shielding of molecules by, 391, 397
  - silicate absorption features, 379
    - at 9.7 and 18  $\mu\text{m}$ , 381
  - size parameter, 380, 381
  - small grains in, 382
    - transient heating of, 382
  - sublimation temperature of, 378, 384
  - water ice feature at 3.1  $\mu\text{m}$ , 381
  - wide range of grain sizes present in, 381
- interstellar gas
  - average properties of, 363
  - cooling mechanisms, 391
    - bound-bound or bound-free emission, 391
    - bremsstrahlung, 391
    - in gaseous nebulae, 391
    - interstellar dust emission, 391
    - low lying energy levels of common elements, 391
    - molecular line emission, 391
- diagnostic tools
  - 21-cm line emission and absorption, 363–365
  - column depth from X-ray absorption, 370
  - dispersion measure of pulsars, 375–376
  - Faraday rotation of linearly polarised radio signals, 376–378
  - ionised interstellar gas, 370–378
  - molecular radio lines, 365–368
  - neutral interstellar gas, 363–370
  - optical and ultraviolet absorption lines, 369–370
  - permitted and forbidden transitions in gaseous nebula, 371–375
  - thermal bremsstrahlung, 370–371
  - X-ray absorption, 370
- heating mechanisms, 389–390
  - collisions of old supernova shells, 389

- cosmic rays and, 390
- ionisation rate by ionisation losses, 390
- other types of, 390
- supernova explosions, 389
- ultraviolet radiation of hot stars, 390
- high velocity clouds, 569
- hot component of, 389, 390
- overall picture of, 387–393
  - large scale dynamics, 387–389
- overall state of, 392–393
- thermal instabilities, 393
  - condition for, 392–393
- interstellar gas and magnetic fields, 363–411
- interstellar medium
  - life cycle of stars and, 363
  - phases of, 392
    - cold neutral medium, 392
    - coronal gas, 392, 393
    - diffuse clouds, 392
    - giant molecular clouds, 392
    - HI clouds, 392
    - intercloud medium, 392
  - two-phase model for, 393
- interstellar molecules, 21
  - hydroxyl molecule OH, 22
  - line emission of, 18
- Introduction to Active Galactic Nuclei* (Peterson), 639
- An introduction to the ionosphere and magnetosphere* (Ratcliffe), 334
- invariant four-volume, 264
- invariant four-volume in four-momentum space, 264, 274, 275
- inverse  $\beta$ -decay, 421, 440, 441
- inverse Compton scattering, 261–268, 286, 534, 617
  - average energy of scattered photons, 267
  - derivation of formulae for, 261–267
  - energy density of radiation in moving frame, 262–264
  - geometry of, 261, 262
  - maximum energy of scattered photon, 267
  - of radio, infrared and optical photons, 267
  - similarity of loss rate to synchrotron loss-rate, 265, 288
  - spectral index of radiation of a power-law distribution of electron energies, 266
  - spectrum of scattered radiation by a single electron, 266
  - total energy loss rate of, 265
- inverse square laws of electrostatics and gravitation, 165
- ion-acoustic instability, 359
- ionisation loss formula
  - adapted for radiation damage density, 160
- ionisation losses of electrons, 158, 159
  - maximum energy transfer per interaction, 159
- ionisation losses of protons and nuclei, 143–167, 321, 330, 390
  - average energy loss per unit path length, 145
  - Bethe-Bloch formula, 153–154
  - cancer therapy and, 158
  - density effect, 154
  - effects of polarisation of medium, 154
  - energy spectrum of ejected electrons, 148
  - heating of giant molecular clouds and, 143, 158
  - lower limit  $b_{\min}$  to collision parameters
    - classical limit, 146
    - quantum limit, 147
  - mean energy loss rates in different materials, 155, 156
  - minimum loss rate, 154, 155
  - non-relativistic treatment, 144–148
  - nuclear emulsions and, 159–160
  - number of ion-electron pairs produced, 158
  - particle detectors and, 143
  - practical forms of the ionisation loss formulae, 154–158
  - range  $R$  and, 155, 157
  - relativistic treatment, 149–154
  - stopping power, 155
  - straggling, 158
  - upper limit  $b_{\max}$  to collision parameters, 145
- ionisation parameter  $U$ , 706, 707
- ionisation potential  $I$ , 147, 148, 155
- IRAM millimetre interferometer, Plateau de Bure, 398
- IRAS galaxies, 810, 811
  - correlation between far-infrared luminosity and radio luminosity, 728, 730
  - star formation and, 654
- IRAS infrared observatory, 386, 654, 728, 781, 807
- Irvine-Michigan-Brookhaven (IMB) neutrino experiment, 426
- ISAAC infrared spectrograph of the ESO VLT, 481
- isothermal carbon core, 71

- isothermal gas spheres, 113–117, 132
  - core radius, 115
  - projected, 115
  - singular, 132, 133
  - structural index, or structural length, 114
  - tidal radius of, 116
  - truncated, 116
- isothermal helium core, 71
- Italian-Dutch BeppoSAX satellite, 773
- Jacobian for transformation between inertial frames of reference, 264
- James Clerk Maxwell Telescope (JCMT), 15, 812
- James Webb Space Telescope (JWST), 11
- Jansky (Jy), 833
- Jeans' instability, 400–401
  - fragmentation within giant molecular clouds, 401
  - time-scale for collapse, 401
- Jeans' length, 401
- Jeans' mass, 401
- Jet Propulsion Laboratory, 427, 428
- Jupiter, mass of, 74, 832
- K-correction, 783, 784, 801
- K20 survey of galaxies, 806, 817
  - very red galaxies in, 818
- Kamiokande solar neutrino experiment, 34, 35, 426
- KASCADE experiment
  - Karlsruhe air-shower array, 633–635
  - SYBILL 2.1 simulations, 634, 635
- Keck 10-metre telescope, 679, 805
- Kelvin-Helmholtz instability, 351, 737
- Kelvin-Helmholtz time-scale, 48
- Kepler's laws of planetary motion, 387, 681, 713
- Keplerian orbits, 492, 497, 498, 670, 671, 673, 677, 679, 689
- Keplerian velocity, 495, 498, 505, 513, 515
- Kerr black holes, 474, 667, 691
  - efficiency of energy conversion, 681
  - $\gamma$ -ray bursts and, 780
  - last stable orbit, 668
  - maximum angular momentum of, 668
  - maximum energy release, 476, 477, 485, 668
  - maximum redshifts of radiation from last stable orbit, 692
  - maximum rotational energy which can be extracted from, 668
  - predicted line shapes of fluorescent 6.4 keV line, 690
  - surface of infinite redshift, 668
  - maximally rotating case, 668
- Kerr metric, 474, 475
- kinetic energy per nucleon, 198
- ionisation losses and, 154
- King profiles for mass distribution in clusters, 116, 117
- Kirchhoff's law, 371
- Klein–Nishina cross-section, 260–261, 291
- Kompaneets equation, 126, 272, 275–283, 285
  - 'current' of photons in phase space and, 276
  - diffusion coefficient for photons in phase space, 277
  - diffusion of photons in phase space and, 277–278
  - expansion to higher orders in  $\partial n/\partial x$ , 286
  - formation of power-law spectrum by thermal processes, 280
  - formation of Wien peak, 278–280
  - induced scattering and, 275
  - Monte Carlo solutions of, 279
  - photon conservation and, 276
  - power-law solutions of, 280–282
  - recoil effect and, 276, 277, 280
  - recoil effect and induced scattering, 277
  - solutions for  $\hbar\omega \gg kT$ , 280
  - spectra of X-ray sources and solutions of, 278–282
- Kramers opacity, 502, 503
- Kruskal coordinates, 473
- Kuiper Airborne Observatory, 15, 391
- Lagrangian formulation of classical dynamics, 200
  - action integral in, 200
- Laing–Garrington effect, 663
- $\Lambda$ CDM model of galaxy and structure formation, 819–823
  - problems with
    - accounting for Faber–Jackson relation and Tully–Fisher relation, 821
- Lane–Emden equation, 114, 435, 436
- Laplace's equation, 464
- Large Bright Quasar Survey, 643
- Large Hadron Collider (LHC), 139
- Large Magellanic Cloud, 137
  - distance from observations of SN 1987A, 430



- Larmor's formula for radiation of accelerated electron, 173, 255, 408, 410
- laser emission, 853
- Laser Interferometer Gravitational-Wave Observatory (LIGO), 36
- last stable circular orbit, 472, 473, 476, 477
- late-type galaxies, 87, 89
- 'leaky box' model, 592
- Lectures on Physics, Vol. III* (Feynman), 272
- Leiden-Berkeley Deep Survey (LBDS), 791
- Lexan polycarbonate, 161
- Liénard-Wiechert potentials, 176, 221, 223, 292
- doppler shift factor in, 223
- lifetimes of stars of different mass, 394
- light echo technique, 421, 596
- light, L, group of elements, 555
- light-year, definition, 829
- line blanketing, 97
- Lockman Hole survey field, 794
- long period variables, 82
- Lorentz factor, 152, 154, 159, 195, 198, 213, 232, 245, 323, 471, 549, 564, 576, 577, 581, 582, 586, 746, 856
- Lorentz force, 195, 200, 465
- Lorentz gauge, 175
- Lorentz transformations, 170, 624, 855
- inverse, 153, 263
- Lorentz transforms for electric and magnetic fields, 149–151, 214–215
- Los Alamos National Laboratory, 771
- Low Ionisation Nuclear Emission Regions (LINERS), 653, 675, 702
- low-mass X-ray binaries, 522–529, 535
- accretion disc corona, 524
- dependence of observed properties on angle of inclination, 523
- eclipses and 'dips' in X-ray light curves, 522, 523
- quasi-periodic oscillations (QPOs), 527–529
- models for, 528–529
- thick absorbing screen about accretion disc, 524, 525
- X-ray burst sources (bursters), 525
- comparison of accretion and thermonuclear runaway luminosities, 525
- properties of, 525
- Type I, 525–527
- Type II, 527
- X-ray colour-colour diagram for, 528
- luminosity
- definition of, 836
- luminosity classes for stars, 42, 43
- luminosity distance, 682
- luminosity function of galaxies, 787
- luminosity function of stars, 393–394
- luminosity indicators for stars, 42, 43
- luminosity-temperature diagram for stars, *see* Hertzsprung-Russell diagram
- luminous infrared galaxies
- evolution of, 809
- N1-015
- spectral energy distribution of, 807
- luminous infrared galaxy N1-015
- spectral energy distribution of, 809
- Lundquist number, 357
- Lyman continuum absorption, 24
- Lyman limit for hydrogen, 24
- M31 (Andromeda Nebula), 101
- nuclear regions of, 673–674
- compact ultraviolet star cluster in, 673
- mass of black hole in, 673
- mass-to-light ratio in, 673
- M87 (NGC 4486), 25, 87, 640, 673, 725, 726, 757, 758
- black hole in nucleus of, 673–675
- mass of, 673–675
- high energy astrophysical activity in, 673
- jet in, 640
- non-thermal optical jet of, 87
- velocity dispersion of stars in nuclear regions of, 673
- anisotropy of, 673
- M106 (NGC 4258)
- black hole in nucleus of, 675–678
- inevitability of, 678
- mass of, 678
- mass density in nucleus of, 681
- molecular torus in central regions of, 678
- water maser emission in, 675, 676
- conditions for, 676
- measurement of centripetal acceleration and, 677, 678
- rotation curve derived from, 676, 677
- Mach number,  $M$ , 347, 493, 495, 606, 622, 631, 633, 734
- Alfvén, 629
- MACHO project, 136, 137
- MACHOs, 136
- mean mass of, 137
- Magellanic Clouds, 487



- MAGIC  $\gamma$ -ray telescope, 771
- magnetars, 458
- magnetic fields in, 458
- magnetic buoyancy, 352–354
- formation of magnetic loops and, 354
  - in a plane-parallel stratified atmosphere, 353
- magnetic dipole radiation, 462, 464, 465
- pulsars and, 446
- magnetic field fluctuations in interplanetary medium
- power spectrum of, 202, 203, 205
- magnetic field, energy density of, 336
- magnetic field, Galactic, 248
- magnetic fields
- in extragalactic radio sources, 20
  - slowly varying, 197, 199, 200
- magnetic fields in our Galaxy, *see* Galactic magnetic field
- magnetic fields in supernova shock fronts, 628–629
- Bell-Lucek instability and, 628, 629
  - equipartition with energy in high energy particles, 629
  - generation of strong, 628
  - instability mechanisms for field amplification, 629
  - X-ray emission from supernova shock fronts and, 628
- magnetic fluctuations generated by Alfvén and hydromagnetic waves in interstellar medium, 205–207
- physical model for, 205
- magnetic flux freezing, 334–344, 443, 464, 504, 570, 628
- change of magnetic flux density with density of plasma, 340
  - diffusion time for magnetic field in a plasma and, 340
  - magnetohydrodynamic approach, 337–342
  - physical approach, 334–337
  - similarity to adiabatic motion of charged particles, 201
- magnetic lines of force
- Faraday's concept of, 352
  - magnetic flux freezing and, 334
- magnetic lines of force, reconnection of, *see* reconnection of magnetic lines of force
- magnetic mirroring, 199
- in the Earth's radiation belts, 199
- magnetic moment  $\mu$  of the current loop, 198
- Magnetic reconnection* (Priest and Forbes), 360
- magnetic reconnection, *see* reconnection of magnetic lines of force
- magnetic Reynolds' number, 341, 342
- 'longitudinal', 357
  - Lundquist number and, 357
- magnetic rigidity, *see* rigidity  $R$
- magnetic tubes of force, 352
- magnetoactive medium, 376
- magnetohydrodynamics
- aspects of, 327–360
  - derivation from microscopic description of particle dynamics in a magnetic field, 201
  - equations of, 337–338
    - entropy equation, 338
    - equation of continuity, 337
    - force equation, 337
    - Maxwell's equation, 337
    - Ohm's law, 337
- magnetosphere of Earth, 349–352, 354, 730
- collisionless plasmas in, 351
  - collisionless shocks in, 352
    - plasma wave interactions in, 352
- magnetopause, 350
- magnetosheath, 351
- magnetotail, 351, 354
- neutral sheet, 351
- plasma sheet, 351
- shock wave discontinuity in, 351
- magnitude
- absolute, definition of, 836
  - apparent, definition of, 833
  - bolometric absolute, definition of, 836
  - bolometric apparent, definition of, 834
- magnitudes in optical and infrared astronomy, 833
- MAGNUM programme, 713
- main sequence, 41–44, 49, 54–56, 67–70, 76, 78, 79, 837
- main sequence termination point, 42, 76, 81
- main-sequence lifetimes of sun and stars, 54–56
- Mariner 4, 202
- Markarian galaxies, 648
- catalogue of, 648
- maser action of interstellar molecules, 22
- maser emission, 853
- mass absorption coefficient for high energy photons, 298, 299
- mass conservation, equation of, 45
- mass distribution in galaxies

- determination of, 671
- tracers of, 672
- mass function of a binary system, 454, 479, 480
- mass loss
  - formation of white dwarfs and, 413
  - quiescent, 78
  - rates of for massive stars, 79
- mass-luminosity relation
  - main sequence stars, 41, 54, 56, 76
  - stars, 394, 799
- mass-metallicity relation for galaxies, 97–98
- mass-to-luminosity ratio
  - early-type galaxies, 135
- masses in astronomy, 10, 832
- masses of galaxies, 98
  - rotation curves of spiral galaxies, 101
  - virial theorem for galaxies and clusters, 99–101
- massive galaxies in clusters, 821
- Mathematical theory of black holes* (Chandrasekhar), 469
- Mauna Kea Observatory, Hawaii, 15
- Maxwell's equations, 174, 614
- Maxwellian velocity distribution, 184
- MCG -6-30-15, 489, 669, 685, 687
  - broad asymmetric X-ray fluorescent line in, 687
  - relativistic effects in, 688
- McGill pulsar group, 458
- mean free path, 495
  - for pitch angle scattering, 205
  - of particle in a plasma, 330
  - of a proton in the interplanetary medium, 332
- mean free time between particle collisions in a plasma, 333
- Medium Deep Survey of galaxies (MDS), 805
- medium, M, group of elements, 555, 564
- megamasers, 675, 676
- metallicity  $Z$ , 76, 77, 97
- metals, 43
- meteorites, 161–164
  - constancy of the flux of cosmic rays and, 164
  - exposure ages of, 164
  - fossil tracks of cosmic rays and, 162–163
  - Galactic cosmic rays and, 162, 164
  - history of Solar System and, 161–164
  - Solar cosmic rays and, 162, 164
- Mg<sub>2</sub> index, 97
  - correlation with (B - V) colour, 97
- microquasars, 481, 740–742
  - relativistic jets in Galactic black hole X-ray binaries, 740
- Mie theory of scattering and absorption, 380, 381
- Mikheyev-Smirnov-Wolfenstein (MSW) effect, 63, 65
- Milky Way, 828
- Millennium galaxy catalogue, 91, 92
- Millennium Simulation, 820–822
  - first quasar candidate, 822
- Miller and Scalo initial mass function, 394
- millimetre and submillimetre waveband, 14–18
  - all-sky images in, 15–18
  - Cosmic Microwave Background Radiation in, 15
  - molecular lines in, 15
  - observing in, 14–15
- millisecond pulsars, 443, 456–457
  - as members of old galactic populations, 459
  - discovery of, 457
  - distribution in the Galaxy, 459
  - in globular clusters, 457
  - limit to spin-up of, 457
  - location on  $P - \dot{P}$  diagram, 457
  - magnetic fields in, 457
  - space velocities of, 459
  - spin-up of, 457
- minimum energy requirements for synchrotron radiation, 599–603, 640
  - as order of magnitude estimates, 602
  - equipartition and, 601–602
    - limitations of, 601–602
  - filling factor and, 602
  - minimum energy density in particles and magnetic field and, 602
  - minimum total energy, 601
  - simplified estimate for, 602
- Minkowski metric, 469
- MKK spectral classification system, 42
- modified Bessel functions
  - of order 2/3 and 1/3, 227
    - asymptotic expressions for, 231
  - of order zero and one, 180
    - asymptotic values of, 180
- molecular hydrogen
  - distribution in the Galaxy, 388
- molecular radio lines, 365–368

- list of molecules identified by their, 365–367
    - maser action and, 365
    - molecular doubling processes and, 367
    - rotational ladder of, 367, 368
  - molecules in the interstellar gas, 365–368
    - acetylenic, 368
    - CO as a tracer of molecular hydrogen, 368
    - discovery of, 365
    - electronic transitions of, 365, 367
    - glycine, 368
    - in large redshift quasars, 368
    - list of known species, 365–367
    - molecular hydrogen, 368
    - rotational transitions of, 367
    - self-shielding, 368
    - shielding by dust, 367
    - types of, 368
    - unsaturated, 368
    - vibrational transitions of, 367
  - momentum four-vector  $P$ , 152, 153, 169, 170, 857
    - for electrons, 259
    - for photons, 259, 302
  - momentum impulse, 144, 145, 151, 181, 330
  - morphological classification of galaxies, 85–88
  - morphologies of clusters of galaxies, 109–112
  - Mount Hopkins Observatory, Arizona, 13
  - muons
    - decay of, 322
    - mean lifetime of, 323
    - test of relativistic time dilation and length contraction, 323
  - underground
    - measurements of intensity and isotropy of cosmic rays from, 323
  - N-galaxies, 641, 649, 650
  - negative pressure equation of state, 473
  - neutral hydrogen
    - 21-cm line emission of, 20
    - 21-cm map of the Galaxy, 21, 22
    - distribution in the Galaxy, 387–388
  - neutral sheets, 351, 355, 356, 358
    - thickness of, 357
  - Neutrino Astrophysics* (Bahcall), 61
  - neutrino interactions
    - charged current interaction (CC), 64, 65
    - elastic scattering (ES), 64, 65
    - neutral current interaction (NC), 64, 65
  - neutrino oscillations, 63, 138
    - in atmospheric  $\mu$  neutrinos, 65
    - in terrestrial neutrino experiments, 66
    - solar neutrinos and, 63–65
  - neutrinos
    - laboratory limits to the masses of, 138
    - laboratory limits to the number of species of, 140
  - neutrinos, solar, *see* solar neutrinos, 307
  - neutron capture  $\gamma$ -ray line at 2.223 MeV, 318, 320
  - neutron degeneracy pressure, 84, 413
  - neutron drip, 440
  - neutron production by  $(\gamma, n)$  interaction, 326
  - neutron stars, 20, 76, 84, 341, 413, 439–443
    - binding energy of, 414, 599
    - cooling by neutrino emission, 460
    - diffusion time for magnetic field from, 341
    - discovery of, 444–458
    - ellipticity  $\epsilon$  due to rotation, 463
    - galactic population of, 458–460
    - in X-ray binary systems, 450–454
    - internal structure of, 439–443
      - core region, 442
      - inner crust, 442
      - inverse  $\beta$ -decay and, 440
      - neutron liquid phase, 442
      - outer crust, 441
      - superconductivity and superfluidity and, 442–443
      - surface layers, 441
      - zones within, with increasing density, 441–442
  - magnetic dipole moment of, 446
  - magnetic flux density of, 341
  - mass estimates in binary star systems, 455, 456, 479, 481
  - predicted surface temperatures, 460
  - rotating neutron superfluid and, 463
    - pinning of quantised vortices in, 464
    - quantisation of angular momentum, 463
  - rotation of, 443
  - rotational break-up speed, 443
  - scale height of atmospheres of, 460
  - thermal emission of, 460–461
  - ‘truly isolated’, 461
  - X-ray emission from surfaces of, 460, 461
- neutronisation, 440
- Newton’s law of gravity, 832
- Newton’s laws of motion, 832

- Nobeyama Radio Observatory, 45 m millimetre telescope, 396
- noise power, 853
- fluctuations of, 853
  - in thermal equilibrium, 852
- noise temperature
- of the receiving system  $T_{\text{sys}}$ , 854
- non-electromagnetic astronomies, 34–36
- astroparticle physics, 36
  - gravitational waves, 35–36
  - neutrino astrophysics, 34–35
- non-linear diffuse shock acceleration, 629–633
- precursor region in, 630–633
  - electron and ion temperatures in, 632
  - $H\alpha$  emission due to charge exchange interactions, 632
  - $H\alpha$  emission from, 632, 633
  - self-similar solutions for, 630, 631
- non-relativistic gyroradiation, 216–219
- energy loss rate by, 216
  - linear and circular polarisation of, 216, 235
- non-thermal radiation, 5, 213
- non-thermal sources
- spectra of, 233
- norm of four-vector, 177, 856
- north celestial pole (NCP), 825–827
- North Polar Spur, 247, 407
- northern celestial hemisphere, 826
- novae, 419, 521–522
- nuclear  $\gamma$ -ray lines
- important, 319, 320
- nuclear cascades, 302
- number of particle produce in, 309
- nuclear deflagration, 522
- nuclear emission lines, 315–320
- $^{44}\text{Ti}$  from supernova remnant Cas A, 317, 318
  - asymptotic giant branch stars, 316
  - collisional excitation of nuclei, 318–320
    - cross-sections for, 318, 319
    - in the interstellar medium, 318, 320, 321  - decay of radioactive isotopes, 315–317
    - astrophysically important examples of, 315, 316
    - conditions for observability of, 315–316  - diffuse  $^{26}\text{Al}$  and  $^{60}\text{Fe}$  emission from the Galaxy, 316, 317
  - diffuse  $^{26}\text{Al}$  emission from the Galaxy, 317
  - explosive nucleosynthesis and, 316
  - supernovae and, 316
  - Wolf-Rayet stars and, 316
- nuclear emulsions, 159, 160
- development of, 159
  - discovery of elementary particle and, 160
  - silver bromide crystals, AgBr, 159
- nuclear energy generation rates in stars, 48–50
- nuclear interaction cross-section, 307, 308
- nuclear interactions, 307–326
- cosmic rays in the atmosphere, 321–326
  - high energy astrophysics and, 307–310
  - multiple scattering within nuclei, 308
  - neutron production in, 308
  - nuclear emission lines, 315–320
  - nucleus–nucleus collision, 309–310
  - pion and strange particle production in, 308, 309
  - spallation cross-sections, 310–315
  - spallation fragments, 308
- nuclear interactions in the atmosphere
- mean free path for, 309
- nuclear interactions of high energy particles
- with nuclei of atoms and molecules, 143
- nucleonic cascades, 571, 577
- particle detectors and, 323
  - total ionisation as a measure of energy of primary cosmic ray, 323
- nucleosynthesis
- explosive, 422–424
  - in massive stars, 413
  - late stages of, in massive stars, 421
  - primordial, 136, 547
  - shell burning, 419
  - steady-state, 422–424
  - synthesis of isotopes and, 422, 423
- Nucleosynthesis and chemical evolution of galaxies* (Pagel), 543
- nucleus, radius of, 307
- Nyquist's theorem, 852
- OB supergiant mass-loss rates, 529, 531
- observability of the sky in different astronomical wavebands, 5, 6
- observations in cosmology for Friedman world models
- flux density–redshift relations
  - for starburst galaxies in the submillimetre waveband, 810, 811
- occupation number, 264, 272–275
- as a Lorentz invariant, 274, 755
  - for Bose-Einstein distribution, 273
  - for Planck distribution, 273

- in Rayleigh-Jeans region of Planck spectrum, 273
  - mean, 273
  - spontaneous and induced processes and, 272
- OH/IR stars, 82
- old red galaxies, 806, 817–819
  - constancy of masses with redshift, 818
  - early formation of stellar populations of, 819
  - early starbursts, 818
  - evidence for old stellar populations in, 818
  - evolving stellar mass density and, 817
  - massive, 817–819
  - selected in the K waveband, 817
  - star-forming galaxies at large redshift and, 818
  - stellar masses as a function of redshift, 817
- ‘onion-skin’ chemical structure of massive stars, 72
- opacity  $\kappa$  of stellar material, 50–54
- optical and infrared wavebands used in ground-based astronomy, 835
- optical and ultraviolet absorption lines, 369–370
  - curve of growth of, 369
  - D lines of sodium, 369
  - deficit of heavy element in the interstellar gas, 370
  - deuterium and, 370
  - Doppler broadening of, 369
  - equivalent width of, 369
  - H and K lines of calcium, 369
  - highly ionised OVI and, 370
  - molecular hydrogen and, 369
  - radiation or natural broadening of, 369
- optical depth for radiation  $\tau$ , 188
- optical polarisation of starlight, 404–407
  - alignment of interstellar grains and, 405–407
  - as a function of galactic coordinates, 407
  - degree of polarisation correlated with extinction, 405
  - maximum degree of, 404
  - parallel to minor axis of grains, 405
- optical waveband, 7–10
  - all-sky images in, 7–10
  - observing in, 7
- optically, violently variable (OVV) objects, 651
  - associated with FR2 radio sources, 653
  - properties of, 652
- Orbital Astronomical Observatories II (OAO-II), 369
- orbital migration, 75
- origin of cosmic rays in our Galaxy, 585–611
- The origin of the chemical elements* (Tayler), 543
- OSO III satellite, 28
- overdensity of galaxies about any galaxy, 92, 93
- OVRO Millimetre Array, 127, 128
- oxygen burning, 71
- 
- $P(D)$  distribution, 787, 794
- P-Cygni profiles, 78–81, 521
  - mass outflows and, 78, 79
- p-p chain, *see* proton-proton chain (p-p chain)
- paleogeomagnetic studies of Earth’s magnetic field, 326
- Palomar 200-inch telescope, 7, 645
- parallax-second (or parsec, pc), definition, 829
- parallaxes, 829
- Parker instability, 569–571
  - buoyancy and, 570
- Parker’s loops, 570
- Parkes Radio Telescope, 448
- Parkes Selected Region (PSR) sample, 791
- Parseval’s theorem, 177–178, 295
  - applied to magnetic field fluctuations in interplanetary medium, 203
  - spectral distribution of the radiation of an accelerated electron and, 177–178
- partial spallation cross-sections, *see* spallation cross-sections, partial
- particle-antiparticle annihilation, 302
- Pauli exclusion principle, 139
- $\dot{P}$  versus  $P$  diagram for pulsars, 448–450
  - ‘graveyard’ region of, 450
  - as an evolutionary sequence for pulsars, 449
  - death line for pulsars on, 450, 457
  - pulsar equivalent of the Hertzsprung-Russell diagram, 448
- peculiar galaxies, 88
  - strong gravitational encounters or collisions, 88
  - tails associated with prograde encounter between galaxies, 88
- Penrose process, 477
- perchloroethylene  $C_2Cl_4$ , 61
- perfect gas law, 120
- permitted and forbidden transitions in gaseous nebula, 371–375

- excitation by ultraviolet emission of hot stars, 371
- photoexcitation and photoionisation, 371
- temperature of emitting regions,  $T_{\text{gas}} \approx T_{\star}$ , 371, 390, 391
- permittivity
  - relation to refractive index  $n$ , 294
- Perseus cluster of galaxies, 26, 125, 727, 739, 821
  - $\text{Ly}\alpha$  and  $\text{Ly}\beta$  emission lines of highly ionised iron,  $\text{Fe}^{+25}$  in, 185, 186
  - X-ray bremsstrahlung of hot intracluster gas in, 185
  - X-ray spectrum of, 185
- Petrosian r-band luminosity, 94
- Petschek mechanism of magnetic reconnection, 358
- phase space
  - elementary volume of, 273
- photo-pair production, 581–583
- photo-pion production, 581, 582
  - threshold for, 581
- photodisintegration of iron nuclei, 421
- photoelectric absorption, 251–255
  - cross-sections for, 251–255
  - spectra of X-ray sources at energies  $\varepsilon \sim 1$  keV, 251–255
- photoelectric effect, 251
- photoionisation
  - cross-section for hydrogen atoms, 371
- photon loss processes
  - summary of absorption coefficient for, 299
- photon–photon collisions, 302
  - as a source of opacity for high-energy  $\gamma$ -rays, 303
  - cross-section for
    - in the regime  $\bar{\varepsilon} \approx m_e c^2$ , 303
    - in ultrarelativistic limit, 303
  - threshold energy for electron–positron pair production, 302–303
  - examples of, 303
- photon–photon interactions with extragalactic background radiation
  - cut-off at  $\gamma$ -ray energies, 769, 770
  - limits to the extragalactic background intensity in the optical and infrared regions, 771
- photonuclear interactions for nuclei
  - disintegration of the nuclei and, 583
  - giant dipole resonance for, 583
- physical constants in SI units, 854, 856
- The physics of fully ionised gases* (Spitzer), 327, 331
- The physics of plasmas* (Fitzpatrick), 327
- Physics of shock waves and high-temperature hydrodynamic phenomena* (Zeldovich and Raizer), 344
- Pioneer missions of NASA, 344
- pionisation, *see* cosmic rays in the atmosphere, pion production
- pions
  - decay of, 322
  - mean lifetime of, 322
- pitch angle, 196, 203, 213, 215, 217, 220, 222, 224, 227–230, 234–236, 245
  - isotropic distribution of, 215, 235
- pitch angle scattering, 205
  - physical model for, 204
- PKS 2155-304, 770
- Planck spectrum of black-body radiation, 5, 186, 187, 270, 272, 273, 383, 500
  - as a solution of Kompaneets equation, 278
- plane of the ecliptic, 825, 826
- planetary nebulae, 82–83
  - central stars of, 83
  - evolutionary tracks for, 83
  - images of, 82
  - mass loss and, 82
  - mass loss events and the structures of, 83
- plasma frequency, 327–329, 375, 376
  - angular, 327
- plasma physics
  - aspects of, 327–360
  - elementary concepts in, 327–334
- Plasma physics for astrophysics* (Kulsrud), 327, 360
- plasma sheet, 351
- Plummer model for elliptical galaxies, 116
- point-spread function, 844
- Poisson statistics, 849
- Poisson's equation
  - for gravity, 116, 401
  - in electrostatics, 329
- polars, 218
- polycyclic aromatic hydrocarbon (PAH) molecules, 381–383, 807, 809
  - planes of hexagonal benzene rings and, 383
  - unidentified infrared lines and, 382
- polytropes, 435
- polytropic index, 435
- positron production mechanisms, 302–305
- positronium atoms, 304

- positrons
  - sources of, 302
    - creation of electron–positron pairs, 302
    - decay of  $\pi^+$  pions, 302
    - decay of long-lived radioactive isotopes, 302
- Poynting jets, or outflows, 762, 763
  - highly relativistic collimated flows and, 763
  - plasmoids and, 763
  - velocities of, 762
- Poynting vector, 172, 294, 295
- Poynting's theorem, 256
- precessing jet in SS 433, 741, 742
- principle of detailed balance, 186, 239
- Principle of Equivalence, 470
- principle of jump rate symmetry, 272, 273
- Principles of Optics* (Born and Wolf), 838
- probability density function, 849
- projected surface brightness, 121
- projections of celestial sphere onto a plane, 825–829
- proper acceleration, 173, 177
- proper time
  - in general relativity, 470–472
  - in special relativity, 470
- proton decay, 426
- proton–proton chain (p–p chain), 49, 53, 55, 56, 60, 63
  - pp1, pp2 and pp3 branches, 60, 61
- protostars, 341, 383–386
  - accretion shock in, 384
  - as intense far infrared sources, 384
  - diffusion time for magnetic field from, 341
  - dust photosphere of, 384
  - hydrostatic core of, 383, 384
  - release of binding energy by far infrared emission, 384
  - spectra of, 384, 385
  - structure of, 383–384
- pulsar glitches, 447, 461–464
  - changes in moment of inertia of neutron star and, 461
  - glitch function, 462
  - healing parameter, 462
  - migration of quantised vortices and, 464
  - spin-up following, 462
    - time constant of  $\tau_c$ , 462, 463
  - starquakes and, 463
  - two-component model of interior of neutron star and, 461, 463
- pulsar magnetosphere, 464–467, 742
  - beaming of radio emission and, 466
  - closed field lines in, 465
  - corotation radius, 465
  - critical field line, 466
  - dominated by electromagnetic forces, 465
  - inevitability of fully conducting plasma surrounding, 465
  - inner and outer acceleration gaps, 467–469, 616
    - limited by pair production processes, 616
    - radio emission from, 468
  - light cylinder, 465, 466
  - magnetic field distribution in, 465, 466
  - open field lines in, 465, 466
  - polar cap regions of, 465, 466
    - potential differences in, 467
  - sparks in, 468
  - space charge distribution in, 465
  - strong electric fields in, 465
  - zero charge cones, 465, 466, 468
- pulsars, 376
  - ages from braking index, 447
  - ages of, 447
  - anomalous X-ray, 458
  - as magnetised, rotating neutron stars, 444, 446, 464
  - as spiral arm populations, 459
  - associated with supernova remnants, 459
  - binary, 454–456
  - dispersion measures of, 459
  - high velocities of
    - asymmetric supernova explosions and, 509
    - disruption of binary systems and, 509
  - incoherent infrared, optical and X-ray emission from outer gap regions, 468
  - kinematic ages of, 459
  - large velocities due asymmetric collapse of core-collapse supernovae, 459
  - large velocities due to disruption of close binaries, 459
  - luminosity function of, 460
  - magnetic flux density from slow-down rate, 448–450
  - millisecond, 443, 456–457
  - normal radio, 444–450
  - $\dot{P}$  versus  $P$  diagram, 448–450
  - radio emission of, 443
  - rate of loss of rotational energy, 448
  - rates of formation of, 460
  - scale-height in the Galaxy, 459
  - space densities of, 460



- space velocities of, 459
- spin-up, 449, 513, 515
  - by accretion, 515
  - maximum rotation rate and, 515
- spin-up rate–luminosity relation, 514, 515
- timing noise, 461
- quantisation of rotational angular momentum, 367
- quantum theory of gravity, 473
- quark matter, 442
- quasar spectra
  - blue bump, 698–700
  - Comptonisation and, 700
  - Lyman- $\alpha$  emission line, 643–645
  - Lyman- $\alpha$  forest and, 644
  - optical spectrum of
    - synchrotron radiation and, 700
  - prominent emission lines in, 644
- quasars, 20, 641–648, 698
  - bolometric luminosities of, 681
  - bolometric luminosity function of, 682
  - composite optical spectrum for, 643, 697
  - discovery of, 641–642
  - early formation of supermassive black holes in, 819
  - infrared, 699
  - interacting galaxies underlying, 655, 656
  - low-luminosity, 647, 792
  - luminosity function of, 681
  - number counts of, 682, 683
  - optical-to-X-ray spectra of, 699
  - radio quiet, *see* radio quiet quasars
  - ratio of black hole to spheroid masses, 819, 821
  - techniques for discovering radio-quiet, 642–658
  - 3CR sample of radio, 789
- Quasars and Active Galactic Nuclei – an Introduction* (Kembhavi and Narlikar), 639
- quasi-stellar radio sources, *see* quasars
- Quasi-stellar Radio Sources and Gravitational Collapse* (Robinson, Schild and Schücking), 642
- radiation damage, 143, 160–164
  - in plastics and meteorites, 160–164
  - polymers and, 160
- radiation damage density  $J$ , 160, 161
- radiation of accelerated charged particles, 169–178
  - from Maxwell's equations, 174–176
  - J.J. Thomson's treatment, 170–173
  - loss rate of, 214
  - non-relativistic, 170–176
  - polar diagram of, 173
  - polarisation of, 173
  - properties of, 173
  - relativistic, 176–177
  - relativistic invariants, 169–170
    - total energy loss rate, 169, 170, 190
  - total energy loss rate of, 173
- radiation pressure in stars, 51, 54
- Radiation Processes in Astrophysics* (Rybicki and Lightman), 141
- radiation resistance, 853
- radiation-driven pulsational instability for massive stars, 79
- radiative transport of energy in stars, 50–52
- radio emission of spinning dust grains, 408–410
  - Galactic background radiation and, 409–410
- radio emission of the Galaxy, 246–249, 854
  - comparison with predicted emission using local energy spectrum of cosmic ray electrons, 248
  - determination of radio spectrum and radio emissivity, 247–248
  - discovery of, 639
  - radio emissivity of, 248
    - in direction of opaque regions of ionised hydrogen, 248
  - radio spectrum of, 247
  - synchrotron radiation and, 640
- radio galaxies, 640
  - broad-line (BLRG), 650, 651, 698, 789
  - differences between broad-line, and Type 1 Seyfert galaxies, 650–651
  - discovery of, 19
  - emission spectra of
    - large diffuse clouds and, 702
  - energy requirements of, 19
  - evidence for old stellar populations in, 818
  - extended emission line regions in, 651
  - giant elliptical galaxies, 728
  - high energy astrophysics and, 639–640
  - narrow-line (NLRG), 650, 659, 698
  - properties of, 723–728
  - 3CR sample of, 789
- radio map of the sky, 246
- radio pulsars, 20, 84
  - brightness temperatures of, 467



- coherent radiation of, 467
- maser emission of, 467
- radio emission of, 467–469
  - curvature radiation and, 468
  - electron/death line and, 468
  - electron/positron–photon cascades and, 468
- radio quasars, 745
  - properties of, 723–728
- radio quiet quasars, 656
  - counts of, 646, 647, 792
  - cut-off at large redshifts, 645, 793
  - definition of complete samples of, 647
    - completeness of, 647
    - dispersion prism-grating techniques, 645
    - multi-colour photometric technique, 644–645
    - searches for ‘*i*-band drop-outs’, 645, 793
    - searches for Lyman- $\alpha$  and CIV emission lines, 645–646
    - searches for variability of, 646–647
    - ultraviolet excess technique, 643–644
  - discovery of, 642, 792
  - evolution of, with cosmic epoch, 645, 792
  - luminosity function of
    - ‘luminosity evolution’ of, 792
    - evolution of, 647, 792, 793
- radio sources, compact
  - flat-spectrum, 651
  - synchrotron self-absorbed, 651
  - synchrotron self-absorbed, and radio quasars, 651
- radio waveband, 19–23
  - neutral hydrogen and molecular line astronomy, 20–22
  - observing the sky in, 22–23
  - origin of high energy astrophysics and, 19–20
- Radiocarbon*, 325
- radiocarbon dating, 324–326
  - calibration of, 325
    - impact of nuclear test explosions, 326
    - influence of Earth’s magnetic field, 326
    - using coral samples, 326
    - using tree ring dating, 325
  - detection of supernovae in tree-ring data, 326
- radionuclides, 307
- radius of curvature
  - instantaneous, 222, 224, 225, 229
- ram pressure of the intracluster gas, 727
- range *R* of high energy particles, 155
  - in different materials, 157
- rapid or r-process, 72, 424
  - formation of elements beyond the iron peak and, 424
  - proto-neutron stars and, 424
- ratio of specific heat capacities
  - for non-relativistic degenerate gas, 432
- Rayleigh criterion for resolving two point sources, 843
- Rayleigh scattering, 380, 381, 659
- Rayleigh-Jeans region of Planck spectrum, 189, 240
- Rayleigh-Jeans spectrum, 501, 777
- Rayleigh-Taylor instability, 419, 607, 609, 610
- recoil effect, 260, 268, 280
- reconnection of magnetic lines of force, 351, 354–360
  - diffusive time-scale, 358
  - formation of current filaments by tearing mode instabilities, 359
  - ohmic losses, 355
  - Petschek mechanism, 358
  - reconnection velocity, 357, 358
  - self-consistency of models for, 360
  - Sweet–Parker mechanism for, 355–358
- rectangular one-dimensional aperture
  - diffraction pattern of, 840
- red and blue sequences of galaxies, 89–95
  - colour and absolute magnitude, 89–91
  - effect of galaxy environment, 92–93
  - mean stellar age and concentration index *C*, 93–95
  - Sérsic index and colour, 91–92
  - statistics of galaxies belonging to, 95
- red sequence, 89
  - preferentially found in rich cluster environments, 93
  - properties of galaxies of, 89
- Red-Sequence Cluster Survey, 135
- redshift
  - gravitational, 471
- reduced mass of molecule, 367
- Rees diagram, *see* black holes in the nuclei of galaxies, growth of, Rees diagram
- reference frames in standard configuration, 148, 149
- Reissner-Nordstrøm metric, 474
- relativistic aberration, 220, 754
  - formulae, 220, 221
- relativistic beaming, 750–758

- distortions of dipole polar diagram, 755
- foreshortening effects, 757
- frequency shift of relativistically moving source component, 755–756
- relative intensities of identical components ejected in opposite directions, 756
- relativistic ballistic model and, 750–756
  - frequency shift of the radiation, 752–753
  - frequency wavebands, 753
  - kinematics of, 750–752
  - maximum transverse velocity, 751
  - relativistic beaming effects, 752–755
  - solid angles, 754, 756
  - time intervals, 753–754
- relativistic jets, 756–757
  - model dependence, 757
- relativistic transformation of
  - black-body spectrum, 755
  - brightness temperature, 755
  - intensity of radiation, 754–755
  - power-law spectrum, 756
- synchrotron radiation and, 220–222, 226, 232
- synchrotron self-absorption in relativistic jets, 757
- relativistic Doppler shift, 689
- relativistic invariants, 169–170
  - total energy loss rate, 169, 170, 177, 190, 215
- relativistic jets
  - heating of the interstellar gas by, 821
- relativistic kinetic energy, 857
- relativistic length contraction, 182
- relativistic Maxwellian distribution, 240
- relativistic plasma, 20
- relativistic three-momentum, 197, 200, 857
- relativistic total energy, 857
- relativistic transformation of an inverse square law Coulomb field, 149–151
- Relativity: Special, General and Cosmological* (Rindler), 855
- relaxation time of particles in a plasma, 331–333
- retarded potentials, 294
- retarded time, 176, 223
- Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), 318, 320
- reverberation mapping, 709–715
  - cross-correlation functions for, 712–713
  - infrared observations
    - evidence for dusty torus, 714
    - infrared observations of, 713
  - isodelay surface, 710
  - lags determined from, 710, 712
  - stratification of ionisation structure from, 713
  - thermal reprocessing of X-ray emission and, 715
  - transfer function for, 712
  - X-ray emission of Seyfert 1 galaxies, 700
- Reynolds number  $\mathcal{R}$ , 494, 495
- Richtmeyer-Meshkov instability, nonlinear, 629
- right ascension (RA or  $\alpha$ ), 825, 826
- rigidity, or magnetic rigidity,  $R$ , 197, 198, 204, 579
- ring galaxies, 88
- Roche lobe, 502, 506–510, 524
  - overflow, 80, 509, 516, 529, 531
- ROSAT All Sky Survey, 597
- ROSAT X-ray Observatory, 26, 27, 123, 461, 597, 657, 781, 794
  - ultraviolet Wide Field Camera of, 389
  - Wide Field Camera, 24
- Rosseland mean opacity, 52, 502
- Rossi X-ray Timing Explorer (RXTE), 458, 489, 527, 531, 533, 692, 715, 749, 769
- rotation curves of spiral galaxies, 101
  - constancy at large radial distances, 101
- rotation measure, 377, 402–404
  - as a function of galactic latitude, 402, 403
  - pulsar, 403, 404
- RR-Lyrae variable stars, 81
  - masses of, 81
- Sérsic index  $n$ , 91–93
- SAGE solar neutrino experiment, 34
- Sagittarius A\* (Sgr A\*), 678–681, 826
  - angular size of, 679
  - at dynamical centre of the Galaxy, 679
  - infrared counterpart of, 681
  - supermassive black hole in, 826, 827
- Salpeter initial mass function, 394, 800, 813, 814
- SAS-2  $\gamma$ -ray satellite, 28, 552
- scalar potential  $\phi$ , 174
- scale height of an atmosphere, 353
- scattering of charged particles by irregularities in magnetic field, 202–205
- scattering of high energy particles by Alfvén and hydromagnetic waves, 205–207, 567
- Schönberg-Chandrasekhar limit, or mass, 54, 66, 799

- Schechter luminosity function for galaxies  
turnover luminosity  $L^*$ , 818
- Schmidt law of star formation, *see* Schmidt-Kennicutt law
- Schwarzschild black hole, 536
- Schwarzschild metric, 469–475
- Schwarzschild radius, 20, 450, 469, 471, 473, 475, 484, 487, 488, 667–669, 681, 688, 745, 770  
coordinate singularity in, 473  
physical singularity at  $r = 0$ , 473  
X-ray emission from the vicinity of, 26
- SCUBA submillimetre bolometer array, 15, 812
- second-order Fermi acceleration, *see* Fermi acceleration - original version
- Sedov expansion phase of supernova remnant, 605–607, 626  
dynamics of, 606
- seeing disc, 844  
variation in size with wavelength, 844
- self-collision time of particles in a plasma, 331
- semi-analytic models of galaxy formation, 819–823  
as ‘experimental computational astrophysics’, 820  
dust extinction and, 821  
epoch of maximum quasar activity and, 823  
formation of massive black holes in the nuclei of galaxies and, 821  
formation of supermassive black holes and, 823  
in centres of rich clusters, 823  
heating of the intergalactic gas in clusters and, 821  
nuclear starbursts and, 820, 821  
objectives of, 820  
quasars at large redshifts and, 822  
radiative cooling and star formation, 820  
spectrophotometric properties of galaxies and, 821  
supernova explosions and, 820  
two-point correlation function for galaxies and  
for different luminosities and colours, 821
- semi-forbidden transitions in spectra of gaseous nebulae, 374–375  
example of C III], 374  
intercombination lines, 374
- sensitivities of astronomical detectors, 848–854  
in the photon limit, 849–851  
in the wave limit, 852–854  
increasing signal-to-noise by increasing bandwidth and integration time, 853  
optical and infrared detectors, 849–851  
radio and millimetre-wave receivers, 852–854
- Seyfert galaxies, 648–651, 653, 661  
counts of, 647, 792  
differences between Type 1, and broad-line radio galaxies, 650–651  
intermediate types, 649–650  
non-thermal spectra of, 697  
quasars and, 654  
spectropolarimetric observations and unified schemes, 659  
Type 1, 647, 649–651, 655, 656, 658–660, 698, 747, 792  
reverberation mapping of, 709–715  
X-ray spectra of, 692  
Type 2, 649, 650, 655, 658–661, 663, 698  
ULIRGs and, 654  
variability of continuum emission of, 648, 650  
X-ray variability of, 669
- Shapiro time delay, 456
- shear stress, 493, 494
- shock excitation of emission line regions, 715–718
- shock waves, 344–349, 389, 622  
basic properties of plane, 345–348  
collisionless, 352, 627  
conservation relations for, 345  
energy flux conservation, 346  
mass conservation, 345, 346  
momentum flux conservation, 346  
explosions and, 344  
heating of gas to high temperatures and, 348  
Mach number,  $M$ , 347  
oblique, 349  
passage of streamlines through, 350  
role of atomic or molecular viscosities, 348  
shock conditions, 346  
speed of sound and, 344, 345  
stand-off distance, 349  
strong, 347–348, 622, 623  
supersonic piston, 348–349
- shock waves, collisionless, 633

- SI (Système International) system of units, 141
- sidelobes, 844
- signal-to-noise ratio
  - background-limited, 851
  - dependence on size of telescope for different limiting cases, 851
  - detector-noise-limited, 851
  - in the presence of other sources of noise, 850
    - background signal from sky and telescope, 850
    - dark current in the detector, 850
    - read-out noise, 850
  - photon statistics and, 850
  - photon statistics limit, 851
- signature of metric, 856
- silicate dust grains
  - complex dielectric constant for, 381
- silicon burning, 72
- single-line spectroscopic binaries, 453, 480
- singularity theorems of Penrose and Hawking, 473
- sky in different astronomical wavebands, 5
- Sloan Digital Sky Survey (SDSS), 4, 7, 85, 89, 90, 92, 93, 98, 111, 645, 646, 775, 782, 793
- slow or s-process, 72, 73
- Smithsonian SubMillimetre Array (SMA), 15
- Smoluchowski's envelope, 114
- soft  $\gamma$ -ray repeaters, 458
- soft X-ray emission from the Galactic plane, 391
- Solar and Heliospheric Observatory (SOHO) of ESA, 58, 59
- solar flares, 353
  - $\gamma$ -ray spectrum of, 318, 320
- solar luminosity, 40
- Solar magnetohydrodynamics* (Priest), 353
- solar mass, 40, 832
- Solar Maximum Mission, 427, 428
- solar modulation, 204, 205, 247, 390, 549, 552
  - cosmic ray energy spectrum and, 539
  - diffusive-convective model for, 540
  - electron energy spectrum and, 542
- solar neutrinos, 60–66
  - chlorine detector for, 60, 61
  - Davis experiment, 61
  - GALLEX solar neutrino experiment, 63
  - gallium experiments, 63
  - Kamiokande II experiment, 62
  - neutrino oscillations and, 63, 65
  - SAGE experiment, 63
  - solar neutrino problem, 61
  - Sudbury Neutrino Observatory (SNO), Ontario, Canada, 64, 65
  - SuperKamiokande experiment, 62, 63
- solar radius, 40
- solar seismology, *see* helioseismology
- Solar System abundances of the elements, 543–545
  - local interstellar abundances, 543, 544
  - meteoritic abundances, 543
- solar wind, 20, 78, 332, 342–344, 349, 465, 540, 567
  - high-speed winds observed in, 343, 344
  - magnetic field in, 342
  - magnetosphere and the, 349–352
    - drag forces associated with, 351
  - rotating garden sprinkler and trajectories of particles in, 342
  - spiral configuration of magnetic field in, 343
    - out to 20–25 AU, 344
  - typical properties of, 342
- Soudan Cryogenic Dark Matter Search (CDMS), 36
- source function, 244
- south celestial pole (SCP), 825, 826
- South Pole Observatory, 15
- Soviet atomic and hydrogen bomb programme, 275
- spallation, 162–164, 307, 542, 546, 547, 554
  - formation of L from M elements, 556
  - formation of radioactive isotopes in meteorites and, 164
  - formation of rare isotopes in meteorites and, 162, 163
- path length distribution for, 557–558
  - characteristic escape time  $\tau_e$ , 557
  - dependence upon cosmic ray energy, 561
  - exponential, 557
  - Gaussian, 557, 558
  - isotopic anomalies, 563
  - leaky box model for, 558
  - truncated exponential, 558
- path length through interstellar gas for, 555
- production of  $^3\text{He}$  from  $^4\text{He}$ , 556
- products of iron nuclei, 556, 557
- radioactive products, 547
- slab model for, 555, 557, 558

- spallation cross-sections, 310–315, 554
  - dependence upon particle energy, 313–315
    - for iron nuclei, 315
  - features of, 313–315
  - methods of determining
    - experimental, 312
    - Monte Carlo techniques, 312
    - semi-empirical relations, 312
  - partial, 310–315, 554, 555
  - total inelastic, 310, 313
  - weighted average total inelastic, 556
- spallation fragments, 308
  - relativistic, 309, 310
- special relativity
  - notation, 855–857
- specific angular momentum, 471, 473
  - in general relativity, 474
- specific heat capacities, 338
  - ratio of, for perfect gas, 240
  - ratio of, for relativistic gas, 240
- specific volume, 346
- speckles, 845
- spectral energy distribution of galaxies
  - evolution of, 798–800
  - in far infrared and submillimetre wavebands, 810, 811
- spectral index, 234, 239
- spectrum of radiation of an arbitrarily moving electron, 223–224
- spin temperature for 21-cm absorption, 365
- spinning dust grains
  - radio emission of, 408–410
- spiral arm tracers in the Galaxy, 388
- spiral galaxies
  - radio haloes of, 568
- Spitzer Space Telescope, 11, 596, 781, 807
- spontaneous and induced processes, 272, 274
  - rules for, 272, 274
- stand-off distance in shock waves, 344, 349, 350
- standard wavebands used in ground-based astronomy, 834, 835
- star clusters
  - ages of, 76
  - open, 76
- star formation, 84, 393–402
  - angular momentum problem, 400
  - energy problem, 400
  - initial mass function, 393–396
  - issues in the theory of, 400–402
  - Jeans' instability, 400–401
  - magnetic field problem, 400
  - model for, 384–386
  - pre-main sequence evolutionary tracks, 78
  - pre-main sequence stars and, 385, 386
  - regions of, 396–398
  - Schmidt-Kennicutt law, 393–396
- star formation in molecular clouds
  - radiation of heated dust grains at infrared wavelengths as a signature of, 383
  - role of interstellar dust grains, 383
- star-forming galaxies, 383
  - spectrum of, 806
- starburst galaxies, 809
  - ultraviolet spectra of, 813, 814
- starquakes, 463
- stars and stellar evolution, 39–84
  - basic observations of, 39–43
  - equations of energy generation and energy transport, 48–52
  - equations of hydrostatic support and mass conservation, 45–46
  - equations of stellar structure, 53–56
  - evolution of high and low mass stars, 66–76
    - high-mass stars, 69–73
    - low mass stars, 69, 73–76
  - Hayashi tracks, 66–69
  - helioseismology and the internal structure of the sun, 56–60
  - importance of mass loss, 79, 80
  - mass loss, 77–84
    - horizontal branch, 81
    - overall mass loss rate, 83–84
    - P-Cygni profiles and Wolf-Rayet stars, 78–81
    - planetary nebulae, 82–83
  - observations of solar neutrinos, 60–66
  - stellar evolution on the colour-magnitude diagram, 76–77
  - stellar structure, 43–48
  - Sun as a star, 56–66
  - virial theorem for stars, 46–48
- statistical equation of motion for mean drift velocity of electrons in electric field, 333
- statistical equilibrium, 100, 832
- statistical weights, 187, 272
- Stefan-Boltzmann law, 39, 41, 51, 500, 830
- stellar coronae, 78
- stellar evolution
  - formation of isothermal core, 66
  - growth of central helium core, 68

- hydrogen-shell burning, 66
- lower mass limit of  $0.08 M_{\odot}$  for hydrogen burning stars, 73
- of a  $1.3 M_{\odot}$  star, 55
- of a  $15 M_{\odot}$  star, 420
  - core collapse of, 421
  - formation of iron core, 421
  - neutrino luminosity of, 420, 421
- of a  $5 M_{\odot}$  star, 69, 70
- Stellar Magnetism* (Mestel), 464
- stellar structure
  - equations of, 43–56
- stellar winds, 78
- stellar X-ray sources in Magellanic Clouds
  - X-ray luminosities of, 487
- Stokes' theorem, 355
- stopping power, 155
- straggling, 158
- structural index, or structural length, 114
- sub-dwarf stars, 43, 644
- sub-giant stars, 43
- Subaru 8.2-metre telescope, 417, 814
- Subaru Deep Surveys, 814
- submillimetre background radiation, 812
- Sudbury Neutrino Observatory (SNO), 35
- Sun
  - central pressure of, 46
  - corona of, 342
  - main sequence lifetime of, 56
  - minimum central temperature of, 47
  - origin of magnetic field of, 60
  - properties of, 40
  - rotation of, 342
  - speed of sound as a function of radius, 58–60
- Sun as observed from a relativistically moving rocket, 752, 753
- sunspots, 353
- Sunyaev-Zeldovich effect, 282–286, 620
  - Hubble's constant and, 284
  - in hot intracluster gas, 109, 125–129, 284–286, 831
    - distance estimates using, 129
    - in the Rayleigh-Jeans limit, 126
    - shape of spectral distortions, 285, 286
    - spectral shape of distortions, 126
    - spectral signature of, 126
  - SuZIE experiment and measurement of shape of spectral distortions, 286
  - SuZIE experiment and measurement of spectral shape of distortions, 127
  - in Rayleigh-Jeans region of the spectrum, 283
  - increase in energy density of the background radiation, 283
  - physical nature of result in Rayleigh-Jeans spectral region, 284
- super-Alfvénic motions, 352
- superCDMS experiment, 140
- superclustering of galaxies, 111, 112
- superconductivity and superfluidity in neutron stars, 442–443
- supergiant stars, 43
- superluminal motions, 567, 669, *see also* relativistic beaming, 747–750
  - in microquasars, 481
  - observed properties of, 749
    - bends and kinks in jets, 749
    - core-jet structures of, 749
    - range of superluminal speeds, 749
    - streams of components along same axis, 749
  - pattern speed, 750
  - shocks in superluminal jets, 750
  - standard model for, 749, 750
- superluminal source population, *see also* relativistic beaming, 759–763
  - plot of  $\beta_{\text{app}} = v_{\text{app}}/c$  against luminosity  $L$ , 759–761
    - 92% probability limits for, 761
    - aspect curves for, 760–761
    - selection effects and, 759, 760
  - properties of, 761
    - maximum intrinsic luminosity, 761
    - maximum Lorentz factor, 761
- supermassive stars, 695
- supernova light curve
  - radioactive origin of, 317
- supernova rate in our Galaxy, 604
- supernova remnants, 414, 430–431
  - as X-ray sources, 431
  - acceleration of the high energy particles and the generation of strong magnetic fields in, 609
  - acceleration of the high energy particles in, 610
  - adiabatic loss problem, 607–611
  - adiabatic losses and decrease in radio luminosity of, 608
  - adiabatic losses for relativistic gas, 607
  - evolution of, 604–607
  - filled-centre, or Crab-like, 594

- $\gamma$ -ray properties of, 594
- generation of strong magnetic fields in, 609–610
- local energy density of high energy particles due to, 604
- radio properties of, 594–596
  - synchrotron radiation and, 595–596
- Sedov expansion phase of, 605–607, 626
- shell-like, 594, 604
  - adiabatic expansion of, 604, 605
  - contact discontinuity in, 605, 606, 609, 610
  - four stages of evolution of, 604–607
  - intense X-ray emission from, 606, 607
  - late cooling by optical emission, 607
  - reheating by reverse shock in, 607
  - reverse shock in, 605, 606, 610
  - snowplough phase of, 607
  - strong shocks in, 595
  - supersonic expansion of, 606
  - undecelerated expansion phase, 604
  - X-ray emission of, 595
- sources of high energy electrons, 603–604
- sources of high energy particles, 594–599
  - $\gamma$ -ray observations of shell-like, 597–599
  - radio observations of shell-like, 595–596
- supersonically expanding spheres of hot gas, 610
- supernova SN 1987A, 425–430
  - $^{44}\text{Ti}$  energy source for light curve, 317, 429
  - $^{56}\text{Co}$   $\gamma$ -ray emission lines from, 317, 427, 428
  - $^{57}\text{Co}$  energy source for light curve, 429
  - [CoII] and [NiII] infrared emission lines from, 427, 428
- collision of envelope with mass-loss ring, 429, 430
  - observed at optical, X-ray and radio wavelengths, 430
- distance estimate from [OIII] ring, 430
- dust formation in, 429
- light curve of, 425–427, 429
- limits to neutrino mass, 427
- neutrino luminosity of, 427
- neutrinos from, 307
- progenitor of, 425, 426
- rings of [OIII] about, 429
- stellar mass-loss prior to, 426, 429, 430
- Type IIP, 425
- supernova units (SNu), 417
- supernovae, 84, 414–431
  - as sources of high energy particles, 431
  - classification of, 415
  - core-collapse, 419–422
    - bounce mechanism for, 422
    - formation of neutron stars and black holes and, 419–422
    - inhomogeneous expulsion of outer layers, 422
    - kinetic energy release, 421
    - neutrinos from, 427
  - historical, 414–416
  - kinetic energy of ejected material, 430
  - light curves, 416
  - rates of occurrence, 417
  - Type Ia, 416–419, 508
  - Type II, 509
  - Types I and II, 415
    - differences between, 415
  - typology, 414–416
  - supersonic motion, *see* shock waves
  - supersonic piston, 348–349, 606
    - location of shock front relative to, 349
    - supernovae and the, 349, 606
  - Suzuka X-ray satellite, 692
  - Sweet–Parker mechanism of magnetic reconnection, 355–358
    - dissipation rate of, 356, 357
    - effects of gas pressure, 356
    - energy released in, 358
  - SWIFT satellite, 458, 769, 773, 775, 777, 779
  - SWIRE Legacy sample, 809
  - symbiotic stars, 419, 502
  - synchro-Compton radiation, *see also* synchrotron self Compton radiation
  - synchro-Compton radiation and the inverse Compton catastrophe, 288–290, 590, 745, 763–764
    - from time variability of source components, 763, 765
    - relativistic beaming and, 763–765
    - maximum brightness temperatures in compact sources, 763
    - plot of maximum brightness temperature against apparent velocity  $\beta_{\text{max}}$ , 763, 764
    - relativistic beaming and, 763
  - synchrotron radiation, 213–249, 411, 448, 534, 777, 782
    - as the relativistic limit of cyclotron radiation, 217
    - asymptotic expression for emissivity at high and low frequencies, 231



- critical angular frequency for, 229, 230
- critical frequency for, 222, 232–234, 240, 245
- high frequency limit, 231–233
- loss-time for, 733
- map of Galactic, 19
- minimum energy requirements for, 585, 599–603
- polarisation of, 235–239
  - circular, 239
  - fractional, for power-law electron energy spectrum, 238–239
  - spectra of orthogonal polarisations  $I_{\perp}$  and  $I_{\parallel}$ , 236
  - system of coordinates for, 225
  - total energy in polarisations  $I_{\perp}$  and  $I_{\parallel}$ , 237
- radio emission of the Galaxy and, 246–249
- relation between spectral index  $\alpha$  and spectral index of electron spectrum  $p$ , 234
- self-absorption of, 239–244
  - absorption coefficient for, 242–244
  - physical arguments, 239–241
- spectral emissivity of
  - in orthogonal polarisations, 229
  - maximum of, 230, 600
  - total, 229
- spectrum of a power law distribution of electron energies, 233–235
  - emissivity per unit volume, 235
  - full analysis, 234
  - physical arguments, 234
- spectrum of, detailed analysis, 223–233
  - algebra of, 225–229
  - of radiation of an arbitrarily moving electron, 223–224
  - results of, 229–233
  - system of coordinates for, 224–225
- spectrum of, physical arguments, 219–222
- spontaneous transition probability for, 242
- total energy loss rate, 213–215, 231
- useful numerical results, 244–246
  - absorption coefficient  $\chi_{\nu}$  for a random magnetic field, 246
  - critical frequency  $\nu_c$ , 245
  - emission spectrum of a single electron, 245
  - radiation spectrum of a power-law electron energy distribution, 245
  - total energy loss rate, 244
- synchrotron radiation as the scattering of virtual photons, 265
- synchrotron radiation facilities, 230
- synchrotron self-absorption, 239–244, 288, 289
  - absorption coefficient for, 242–244
  - for a randomly oriented magnetic field, 243
  - two-level system for, 242
- evidence for presence of relativistic electrons, 241
- evidence for relativistic electron in compact radio sources, 289
- flat radio spectra as superposition of such sources, 747
- physical arguments, 239–241
- polarisation of synchrotron self-absorbed source, 244
- spectral evolution of expanding sphere, 746
- spectrum of radio source exhibiting, 241
- synchrotron-self Compton radiation, 286–291
  - models of sources of, 290–291
    - homogeneous, 291
    - inhomogeneous, 291
  - synchro-Compton catastrophe, 288–290
- Système International d'Unités (SI units), 854–855
- TAMA gravitational wave experiment, 36
- tearing mode instabilities, 359
- technetium Tc, 73
- telluric absorption, 10
- temperature-frequency relation for black-body radiation, 6
- term diagram for doubly ionised oxygen OIII, 373, 374
- The physics of solar flares* (Tandberg-Hanssen and Emslie), 353
- Theoretical Concepts in Physics* (Longair), ii, 175, 469, 606, 689, 852, 857
- thermal bremsstrahlung, *see* bremsstrahlung, thermal, 370–371, 519
  - absorption in plane of Galaxy, 371
  - absorption, at radio wavelengths, 371
  - at soft X-ray energies from hot component of interstellar gas, 371
  - at X-ray energies from intracluster gas, 371 and FeXXV emission lines, 371
  - at X-ray energies from supernova remnants and FeXXV emission lines, 371
- thermal energy per unit mass, 47
- thermal instabilities, 392–393



- thermal paradox for stars, 48
- thermal time-scale for stars, 48
- thermalisation time of particles in a plasma, 331–332
- thermonuclear runaway, 516, 522, 525
  - stabilisation at about  $10^8$  K, 522
- thick accretion discs, 504–505, 742
  - funnels along polar directions, 504, 505
  - Newtonian rotationally supported vorticity-free torus, 504, 505
  - stability of, 504
- thin accretion discs, 491–504, 718, 719
  - about black holes, 499–500
    - inner boundary condition, 499, 500
  - conditions for, 492–493
  - continuum spectra of, 518
  - detailed models of, 501–504
  - Doppler tomography of, 517, 519
  - emission spectra of, 500–501
    - in black body approximation, 500
  - emission spectrum of, 501, 503
    - in optically thin region, 504
  - energy equation for, 719
  - formation of hot spot, 511, 517, 518
  - instabilities in, 521
  - opacity of material of, 502
  - role of viscosity - the  $\alpha$  parameter, 493–496
  - structure of thin discs, 496–499
  - temperature at inner edge of, 685
  - temperature distribution in, 500–501
  - thermal emission of, 700
  - transition from dominance of gas pressure to radiation pressure, 502, 503
  - X-ray halo about, 685
  - X-ray reflection spectrum of, 686, 687
- Third Reference Catalogue of Bright Galaxies* (de Vaucouleurs et al), 95
- Thomson and Compton scattering, 255–261
- Thomson cross-section, 52, 252, 486
- Thomson scattering, 52, 54, 255–259, 486, 659
  - degree of polarisation of, 258
  - derivation of formulae for, 255–259
  - differential cross-section for, 257, 266, 275
  - Eddington limiting luminosity and, 452
  - for 100% polarised emission, 257
  - geometry of, 256
  - mean free path for, 258
  - optical depth for, 258, 269, 278, 279, 282
  - polarisation of, 258
    - properties of, 257–259
    - total scattering cross-section for, 257
- Thomson scattering cross-section  $\sigma_T$ , 170, 215
- 3C 273, 21, 26, 28, 491, 641, 642, 698, 699, 747, 748
  - Balmer series of hydrogen and, 642
  - optical luminosity of, 642
  - optical variability of, 642
- 3CR radio galaxies, 716, 717, 789, 818
  - alignment effect and, 715, 717
    - photoionisation models for, 717
  - shock models for, 717
- early formation of bulk of stellar population, 819
  - stellar masses of large redshift, 818
- 3CR radio sources, 789, 791
- 3CRR catalogue of radio sources, 661, 664
  - quasars, 684
  - radio galaxies, 684
- threshold detectors, 291
- tidal radius of cluster of galaxies, 114
- tidal radius of galaxies, 133, 135
- time dilation formula
  - in general relativity, 471
- time to reach a given signal-to-noise ratio, 851
- tokamaks, 354
- torque, magnetic, 513, 515
- torque, viscous, 494, 496, 513
- total depth of the atmosphere in  $\text{kg m}^{-2}$ , 193
- transfer equation for radiation, 186, 188, 244
  - in terms of Einstein coefficients for spontaneous and induced emission, 274
  - in terms of occupation numbers, 273, 274
- Transition Region and Coronal Explorer (TRACE)
  - spacecraft of NASA, 339
- transmission function  $G(z)$  of one-dimensional aperture, 838
  - Fourier transform of, 839
  - Gaussian, 844
- transmission function  $T_\nu$  of astronomical filters, 834, 835
- transparency of the atmosphere as a function of wavelength, 5, 6
  - in the infrared and submillimetre wavebands, 10, 15
  - windows in the submillimetre waveband, 15
- tree-ring dating, 325
- Trinity atomic bomb test, 606
- triple- $\alpha$  process, 71
- Tully-Fisher relation for spiral galaxies, 96

- and the distances of galaxies, 96
- infrared, 96
- turbulence
  - magnetohydrodynamic, 496
- 21-cm line emission and absorption, 363–365
  - absorption coefficient for, 364–365
  - column density of neutral hydrogen from, 364
  - emissivity of, 364
  - kinematics of gas in galaxies from, 364
  - spin temperature for, 365
  - spontaneous transition probability of, 363
- 2dF galaxy redshift survey, 644, 782
- 2dF quasar redshift survey, 644, 646, 647, 792, 793
- Two Micron All Sky Survey (2MASS), 13
- 2MRS catalogue, 580
- two-colour diagram for stars, 837
- Type Ia supernovae, 416–419, 521–522
  - as standard candles, 417
  - evolution of colours of, 418
  - formation of  $^{56}\text{Ni}$ , 418
  - light curves
    - radioactive decay of  $^{56}\text{Co}$ , 418
  - light curves of, 416
  - luminosity-width relation, 416, 417
  - most luminous supernovae, 417
  - rates of occurrence, 417
  - redshift-distance relation and, 417
  - thermonuclear explosions and, 415, 417, 418
- UHURU X-ray Observatory, 25, 26, 450, 529, 656, 794
- UK Infrared Telescope, 716
- UK Schmidt Telescope, 644
- ultra-high energy  $\gamma$ -ray telescopes, 300
- ultra-high energy  $\gamma$ -rays
  - detection of, 299–302
- Ultra-Luminous Infrared Galaxies (ULIRGs), 654–656, 811
  - feeding black holes in, 655, 656
  - host galaxies of, 654–655
  - properties of, 654–656
  - starbursts and, 655
  - strongly interacting galaxies and, 655
- ultraviolet waveband, 23–24
  - extreme ultraviolet (EUV), 23
  - observations of resonance lines of common elements, 23
- Ulysses mission of the European Space Agency and NASA, 343, 344
- unification schemes for active galaxies, 658–665
  - BL-Lac objects and FR I radio galaxies, 663–664
  - ionisation cones and, 660
  - obscuring torus and, 658
  - polarisation studies of Seyfert 1 and Seyfert 2 galaxies and, 658–660
  - projection effects and, 658–663
  - radio quasars and radio galaxies, 659–665, 684, 725
    - depolarisation asymmetries and the Laing-Garrington effect, 662
    - one-sided radio jets and, 662
    - polarised optical emission from, 663
    - relativistic beaming and, 662
    - sizes of radio structures of radio quasars and radio galaxies, 663
    - superluminal motions and, 662
  - radio-loud and radio-quiet quasars, 665
    - different host galaxies for, 665
  - relativistic beaming and, 658
  - relativistic beaming of radio cores and, 664
  - Seyfert 1 and Seyfert 2 galaxies, 659, 688
  - Seyfert galaxies and ionising photon counting, 660
  - similarity of X-ray properties of Seyfert 1 and 2 galaxies at hard X-ray energies, 660
  - X-ray absorption properties of Seyfert galaxies and, 660
- unstable stars, 82
- $V/V_{\text{max}}$  or luminosity-volume test, 786–787
  - banded, 787
  - for radio quiet quasars, 792
  - space distribution of galaxies, quasars active galaxies, 786–787
- variance, 849
  - of sum of two quantities, 849
  - total, as the sum of variances, 850
- vector potential  $A$ , 174, 176, 200, 232
- Vela satellites, 28
- velocity cone, 236, 239
- velocity dispersion in galaxies
  - triaxial, 671
- velocity ellipsoid, 671
  - anisotropy of, 672
- velocity four-vector  $U$ , 689, 857
- velocity of Solar System through the Cosmic Microwave Background Radiation, 16

- velocity-distance relation for galaxies, 830
- vernal equinox, 825
- Very Large Array (VLA), 23, 136, 569, 595, 596, 609, 664, 716, 723, 724, 726, 727, 739, 757, 848
- Very Long Baseline Array (VLBA), 675, 737, 742, 747, 760, 765
- Very Long Baseline Interferometry (VLBI), 23, 241, 289, 651, 653, 681, 725, 726, 737, 739, 745–748, 757, 764, 776
- vicinity of the black hole, 697–722
  - accretion discs about supermassive black holes, 718–722
  - alignment effect and shock excitation of emission line regions, 715–718
  - broad-line regions and reverberation mapping, 707–715
    - physical properties of the broad-line regions, 707–709
    - reverberation mapping, 709–715
  - continuum spectrum, 697–700
  - emission line regions – the overall picture, 701–702
  - narrow-line regions – the example of Cygnus A, 702–707
  - prime ingredients of active galactic nuclei, 697
    - fluxes of relativistic material, 697, 698
    - non-thermal continuum radiation, 697, 698
  - secondary phenomena
    - $\gamma$ -ray emission, 697
    - excitation of gas clouds, 697, 698
    - extended radio sources, 697
- violent interstellar medium, 392
  - supernova explosions and, 392
- VIRGO gravitational wave experiment, 36
- virial theorem, 113, 437
  - for galaxies and clusters, 99–101
    - problems of application to observed systems, 100, 101
  - for stars, 46–48, 98
  - galaxies and clusters, 832
- viscosity, 494, 495, 502, 719
  - dynamic or shear  $\eta$ , 493, 495, 496, 498
  - effective, in shock fronts, 627
  - kinematic  $\nu$ , 485, 494, 720
  - turbulent, 495, 496, 501, 504, 511
- viscosity parameter  $\alpha$ , 501, 504, 521, 722
- VLT Antu telescope, ISAAC infrared camera of, 397
- VLT Kueyen Telescope, FORS2 instrument of, 398, 399
- voids in the distribution of galaxies, 800
- Voyager missions of NASA, 344
- W UMa-type binaries, 506
- wave impedance  $Z_0$ , 852
- wavebands used in ground-based astronomy, 835
- wavefront errors, 843, 844
- white dwarfs, 41, 43, 76, 83, 84, 340, 413, 438–439, 483, 644
  - carbon-oxygen, 417, 418
  - cooling curves for, 439
  - cooling times for, 439
  - diffusion time for magnetic field from, 341, 342
  - Hertzsprung-Russell diagram for, 439
  - magnetic flux density of, 341
  - ultimate fate of, 439
  - with carbon-oxygen cores, 438
- white dwarfs, neutron stars and the Chandrasekhar limit, 431–438
- Wien distribution, 271
  - average energy of photons of, 271
- Wien's displacement law, 5
- Wien's law, 280
- Wilkinson Microwave Anisotropy Probe (WMAP), 17
- WIMPs
  - astrophysical limits to the masses of, 139
  - candidates for, 138
  - laboratory detection of, 140
  - laboratory limits to the masses of, 140
  - suppression mechanisms for, 140
- Wolf-Rayet stars, 78–81, 316, 508, 509, 563, 780
  - mass loss rates of, 80
  - WC and WN types, 80
- $W^\pm$  and  $Z^0$  bosons, 140
- X mass fraction of hydrogen, 77
- X-ray absorption, 370
- X-ray absorption coefficient of interstellar matter, 252, 254
  - column depth for, 254
  - optical depth and, 254
- X-ray atomic energy levels, 253
- X-ray background at soft X-ray energies, 26, 27
- X-ray background emission, 657–658
  - at hard X-ray energies

- nature of sources contributing to, 657, 796
- at soft X-ray energies
  - nature of sources contributing to, 794
- contributions of different classes of source to, 797
- spectrum of, 794
- X-ray binary systems, 450–454, 479, 502, 509, 522–537
  - accretion in, 452
  - estimate of mass of neutron stars in, 452–454
  - estimate of masses of neutron stars and black holes in, 453
  - high-mass X-ray binaries, 452, 529–531
    - late O or early B type companion stars, 452
  - low-mass X-ray binaries, 452, 522–529
    - Galactic Bulge sources, 522
    - in globular clusters, 452, 522
  - luminosities of, 452
  - soft X-ray transients, 452
  - symbiotic X-ray binaries, 452
  - typical temperature of, 450
  - X-ray bursters, 452
  - X-ray pulsars, 452
- X-ray emission from supernova shock fronts
  - synchrotron radiation and, 628
- X-ray emission of intracluster gas, 109
- X-ray nova, 531
- X-ray pulsars, 25, 479
- X-ray source spectra and solutions of the Kompaneets equation, 278–282
- X-ray sources
  - binary pulsating
    - as rotating magnetised neutron stars, 488
  - Comptonisation and, 657, 658, 797, 798
  - evolution of luminosity function of, with cosmic epoch, 796
    - similarity to that of optically selected quasars, 657
  - extragalactic, 656
    - correlation between X-ray and optical luminosities, 656
    - counts of, 657
  - populations at soft and hard X-ray energies, 657, 794, 796
  - radio-loud quasars
    - correlation between X-ray and optical luminosities, 657
  - strongly absorbed, 657, 797
    - template spectra for strongly absorbed sources, 658, 797
- X-ray surveys of active galaxies, 656–658
- X-ray waveband, 25–27
  - detectors for, 25
  - observing in, 25
  - sky in, 25–27
- XMM-Newton X-ray Observatory, 27, 119–121, 123, 219, 282, 421, 461, 692, 781, 794
  - EPIC instrument of, 687
- Y mass fraction of helium, 77
- year 2000.0 coordinate system, 825, 826
- YEPUN 8.2-m telescope of the ESO Very Large Telescope, 680
- Yerkes classification scheme for galaxies, 641
- Yerkes spectral classification system, 42
- young FR2 radio sources, 737–738
  - compact steep spectrum sources (CSS), 737
  - compact symmetric objects (CSO), 737, 738
    - ballistic models for, 738
  - early evolution of FR2 sources and, 738
  - gigahertz-peaked spectrum sources (GPS), 737
- Z mass fraction of ‘metals’, 77
- Zeeman splitting
  - of 21-cm line radiation, 410
    - circularly polarised components of, 410
  - of OH absorption lines, 410, 411
- zenith equidistant projection, 7, 827, 828